Self-stabilization of carrier-envelope offset phase by use of difference-frequency generation

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Self-stabilized carrier-envelope offset phase is achieved by use of difference-frequency (DF) generation. The spectrum from a Ti:sapphire oscillator is broadened in a photonic crystal fiber, and a DF (900 nm) between the blue component (490 nm) and the infrared component (1080 nm) is generated. The beat signal between the fundamental and the DF signal is clearly observed. The wavelength of the DF signal can be tuned down to 780 nm, and hence the signal can be used for injection seeding of a Ti:sapphire oscillator.

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Controlling the carrier-envelope offset (CEO) phase of ultrashort light pulses[1–5] is important for nonlinear optics applications, such as high-order harmonic generation, production of x-ray pulses with attosecond duration,[2,6–8] and visible subfemtosecond pulse generation by Fourier synthesis of a multicolor laser.[9,10] Recently, high-precision CEO phase control was achieved by locking a laser cavity to servo-loop feedback based on a phase-tracking system.[1,2,11–13]

The most popular technique for measuring the frequency at which the CEO phase reproduces itself, f_{CEO}, is to measure the interference beat signal between the high-frequency wing and the second harmonic of the low-frequency wing of an octave-spanning spectrum, which has been termed the f-to-$2f$ method.[1,2,14,15] Alternatively, difference-frequency generation (DFG) may also allow one to measure f_{CEO}.[15] Figure 1 shows a schematic for measuring f_{CEO} by use of DFG. The frequency comb of the difference-frequency (DF) signal resulting from mixing of the high-frequency wing of the spectrum, $f_{\mathrm{CEO}} + n_{\mathrm{high}} f_r$ (f_r is the pulse repetition rate of a mode-locked oscillator), and the low-frequency wing of the spectrum, $f_{\mathrm{CEO}} + n_{\mathrm{low}} f_r$, is given by $(n_{\mathrm{high}} - n_{\mathrm{low}}) f_r$; i.e., it is independent of f_{CEO}. Interference between the low-frequency component of the fundamental spectrum and the DF signal yields beating at f_{CEO}[15] by a 0-to-f comparison. The unique feature of the 0-to-f method is that f_{CEO} of the DF is zero without any servo-loop feedback system; i.e., the waveform is self-stabilized in the resultant pulse train.

Self-CEO-phase-stabilized DF pulses were generated recently in an optical parametric amplifier at a low repetition rate.[16] However, to our knowledge, CEO-phase-stabilized optical pulses at the full repetition rate of a mode-locked oscillator has not been demonstrated within the gain band of the oscillator yet. Such a pulse train would benefit precision frequency metrology[17] and might open the way to an all-optical scheme of CEO-phase stabilization by injection seeding.

In this Letter we report, for what is believed to be the first time, CEO-phase-stabilized femtosecond pulses near the center of the gain band of Ti:sapphire at the full repetition rate of the oscillator. The pulse train was produced by DF mixing and used for measuring the CEO frequency of the oscillator by the 0-to-f technique.

In the 0-to-f method the nonlinear crystal for DFG can be either type I [$o + o(\mathrm{DFG}) \rightarrow e$] or type II [$e + o(\mathrm{DFG}) \rightarrow e$]. With a type I crystal, the polarization of the low-frequency component and that of the high-frequency component should be perpendicular to each other. The generated DF signal can be of the same polarization as that of the low-frequency component, and hence DF pulses have the same group velocity as that of the low-frequency pulses even in the crystal, and the delay between the DF pulses is nearly zero. In this case one can easily observe the interference signal between them and obtain the beat at f_{CEO}.[18]

With a type II crystal, the high- and low-frequency components of the radiation have the same polarization and the polarization of the DF is perpendicular to them. In this case the dispersion in the crystal is different for each beam, and therefore the DF pulses have some delay with respect to the low-frequency pulses.

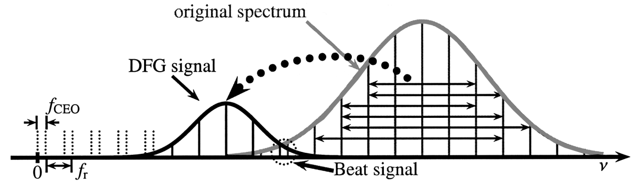

Fig. 1. Scheme for generating a pulse with a self-stabilizing CEO phase.

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This delay reduces the strength of the interference signal between the DF signal and the low-frequency component unless another interferometer for adjustment of the delay between them is incorporated behind the crystal. However, the type II crystal allows us to generate a DF signal that can be selected from the low-frequency component with a polarizer and then used for some phase-sensitive applications, unlike type I crystal. In the experiment we chose the type II configuration because it is more convenient for further applications of the self-CEO-phase-stabilized signal.

The experimental setup is shown in Fig. 2. The light source is a mirror-dispersion-controlled femtosecond Ti:sapphire laser.[19] The pump source of the laser is a 5-W frequency-doubled Nd:YVO_4 laser (Verdi, Coherent). The average output power of the Ti:sapphire oscillator is 350 mW, the repetition rate is 65 MHz, and the pulse duration is ~9 fs. The pulses are precompressed by chirped mirrors and focused into a 2.4-μm-core, 6-mm-long photonic crystal fiber with an achromatic doublet lens designed for optimal performance in the range 600–1000 nm, with a numerical aperture of 0.6. The fiber is azimuthally adjusted to make the polarization of the output constant in the whole wavelength region.[20] The output from the fiber (70 mW) is collimated with an achromatic objective that supports a spectrum in the range 480–1100 nm (ACH40x, Olympus). The spectrum of the fiber is shown in Fig. 3(a). The peaks at 490 and 1080 nm produce the DF signal at 900 nm. The output from the fiber is injected into a Mach–Zehnder-type interferometer that consists of two long-pass filters (Menlosystem) reflecting 490 nm and passing down to 550 nm at 45° and two 30° BK7 wedges for controlling the delay time between the blue and the infrared components. The overlapped beam is passed through a Glan–Taylor polarizer to purify the polarization. The beam is focused onto a 3-mm-thick type II KTP crystal ($\theta = 90°$, $\phi = 45.6°$, EKSMA) that is optimized for $e(1080\text{ nm}) + o(900\text{ nm}) \rightarrow e(490\text{ nm})$ phase matching and collimated with concave silver mirrors with a radius $r = -50$ mm. The electric field of the low-frequency component and that of the DF signal are mixed by a Glan–Taylor polarizer that allows us to control the intensity ratio of both fields. The mixed field is passed through a 10-nm bandwidth interference filter centered at 900 nm (OptoSigma) and then focused onto a multimode fiber by an $f = 50$ mm lens. The output of the fiber is injected into an avalanche photodiode (C5331-02, Hamamatsu). The signal from the detector is analyzed by a spectrum analyzer (E4401B, Agilent Technologies).

A typical rf power spectrum of the combined low-frequency component and the DF signal entering the detector within 900 ± 5 nm is shown in Fig. 3(b). With the polarizer aligned for maximum beating signal, the power of these beat notes is some 40 dB below that emerging at f_r but is still 30 dB above the noise floor. It is worth noting that this value is enough for phase stabilization.[4]

The dependence of the DF on the delay between the blue and the infrared components is shown in Fig. 4. The measurement system consists of a chopper (SR540, Stanford Research), a monochromator (Model 240, CVI), and a lock-in amplifier (Model 5209, EG&G). The DFG spectrum in Fig. 4 changes dramatically because of the large chirp of the pulses. The spectrum is broad in positive delay time (the blue pulses come earlier than the infrared pulses) because the quantity of glass in the path of the blue component becomes smaller and the chirp of the blue component becomes smaller in positive delay time. The spectrum extends down to 780 nm at a +1300-fs delay time. A signal with such a blueshifted DF spectrum is suitable for injection seeding a Ti:sapphire oscillator or for amplification by a Ti:sapphire amplifier. At the optimized time overlap between the infrared and the blue components, the power of the DF is estimated as 2.0 μW (energy, 30 fJ). To amplify the DF signal,

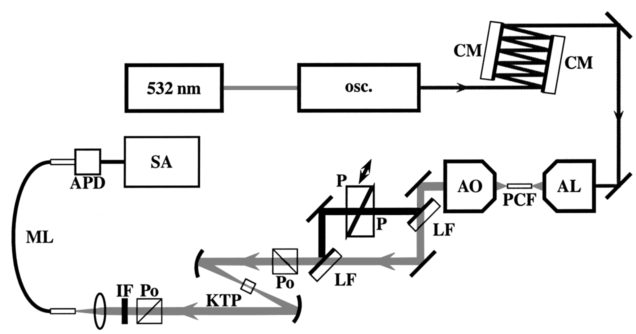

Fig. 2. Schematic of the setup: osc., Ti:sapphire oscillator; CM, chirped mirror; AL, achromatic doublet lens; PCF, photonic crystal fiber; AO, achromatic objective; LF, long-pass filter; P, BK7 prism; Po, polarizer; KTP, type II KTP crystal; IF, interference filter; ML, multimode fiber; APD, avalanche photodiode; SA, spectrum analyzer.

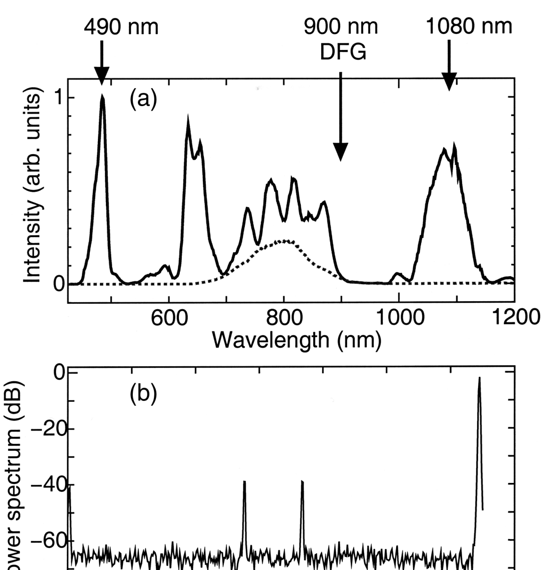

Fig. 3. (a) Spectrum of the photonic crystal fiber on a linear scale (solid curve) and input spectrum to the fiber (dotted curve). (b) rf power spectrum of the combined DF and the fundamental laser radiation at 900 nm with 10 nm of optical bandwidth and 100 kHz of rf bandwidth. The stability of the beat signal is ~200 kHz in 10 min.

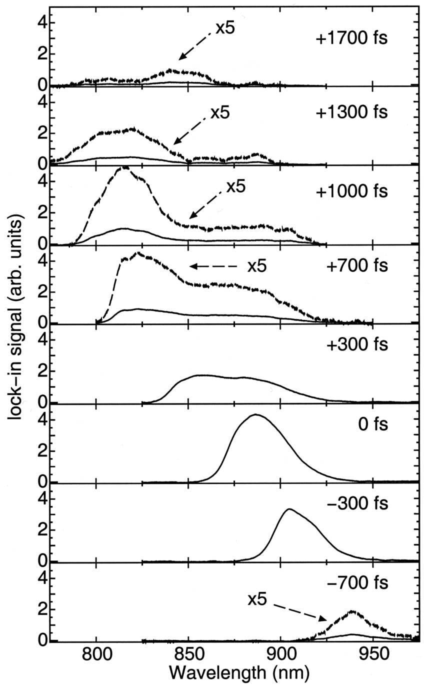

Fig. 4. Delay dependence of the spectrum of the DF. The positive delay means the blue pulses enter the KTP crystal than the infrared pulses.

one must ensure that the peak power of the seed pulses is above the spontaneous-emission level of the gain medium. Hence the DF signal demonstrated in this first proof-of-principle experiment cannot be used directly for a high-gain, millijoule-pulse-pumped Ti:sapphire amplifier. However, if a weaker or cw pump laser is used for the first stage of amplification, the signal may be amplified efficiently. Recently, an erbium-doped fluoride fiber amplifier for 850 nm was developed[21] that may be a promising candidate for amplifying the demonstrated DF signal.

In conclusion, femtosecond pulses with a stabilized carrier-envelope phase have been demonstrated within the gain band of a Ti:sapphire oscillator by means of all-optical techniques, namely, self-phase-modulation and difference-frequency mixing of the oscillator output. The generated phase-stable pulses may—after preamplification—be suitable for seeding high-gain Ti:sapphire amplifiers and (or) the oscillator itself.

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References

1. D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, Science **288,** 635 (2000).
2. A. Apolonski, A. Poppe, G. Tempea, C. Spielmann, T. Udem, R. Holzwarth, T. W. Hänsch, and F. Krausz, Phys. Rev. Lett. **85,** 740 (2000).
3. R. Holzwarth, T. Udem, T. W. Hänsch, J. C. Knight, W. J. Wadsworth, and P. St. J. Russell, Phys. Rev. Lett. **85,** 2264 (2000).
4. A. Poppe, R. Holzwarth, A. Apolonski, G. Tempea, C. Spielmann, T. W. Hänsch, and F. Krausz, Appl. Phys. B **72,** 373 (2001).
5. U. Morgner, R. Ell, G. Metzler, T. R. Schibli, F. X. Kärtner, J. G. Fujimoto, H. A. Haus, and E. P. Ippen, Phys. Rev. Lett. **86,** 5462 (2001).
6. T. Brabec and F. Krausz, Rev. Mod. Phys. **72,** 545 (2000).
7. M. Drescher, M. Hentschel, R. Kienberger, G. Tempea, C. Spielmann, G. A. Reider, P. B. Corkum, and F. Krausz, Science **291,** 1923 (2001).
8. M. Hentschel, R. Kienberger, C. Spielmann, G. A. Reider, N. Milosevic, T. Brabec, P. Corkum, U. Heinzmann, M. Drescher, and F. Krausz, Nature **414,** 509 (2001).
9. Z. Wei, Y. Kobayashi, Z. Zhang, and K. Torizuka, Opt. Lett. **26,** 1806 (2001).
10. Y. Kobayashi, K. Torizuka, and Z. Wei, Opt. Lett. **28,** 746 (2003).
11. S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, T. Udem, and T. W. Hänsch, Phys. Rev. Lett. **84,** 5102 (2000).
12. F. W. Helbing, G. Steinmeyer, J. Stenger, H. R. Telle, and U. Keller, Appl. Phys. B **74,** S35 (2002).
13. A. Baltuška, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hänsch, and F. Krausz, Nature **421,** 611 (2003).
14. L. Xu, C. Spielmann, A. Poppe, T. Brabec, and F. Krausz, Opt. Lett. **21,** 2008 (1996).
15. H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, Appl. Phys. B **69,** 327 (1999).
16. A. Baltuška, T. Fuji, and T. Kobayashi, Phys. Rev. Lett. **88,** 133901 (2002).
17. S. T. Cundiff, J. Phys. D Appl. Phys. **35,** R43 (2002).
18. R. Holzwarth, personal communication, Photonics Institute, Vienna University of Technology (November 19, 2002).
19. T. Fuji, A. Unterhuber, V. S. Yakovlev, G. Tempea, A. Stingl, F. Krausz, and W. Drexler, Appl. Phys. B **77,** 125 (2003).
20. A. Apolonski, B. Považay, A. Unterhuber, W. J. Wadsworth, J. C. Knight, P. St. J. Russell, and W. Drexler, J. Opt. Soc. Am. B **19,** 2165 (2002).
21. B. Sridhar and H. R. D. Sunak, IEEE Photon. Technol. Lett. **8,** 215 (1996).