Investigation of a grating-based stretcher/compressor for carrier-envelope phase stabilized fs pulses

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Abstract: In this work, we experimentally investigate the effect of a grating based pulse stretcher/compressor on the carrier-envelope phase stability of femtosecond pulses. Grating based stretcher-compressor (SC) setups have been avoided in past demonstrations of chirped pulse amplification (CPA) of carrier envelope phase (CEP) stabilized femtosecond pulses, because they were expected to introduce significantly stronger CEP fluctuations than material-based SC systems. Using a microstructure fiber-based detection setup, we measure CEP fluctuations of $\Delta\Phi_{CE,SC}$ = 340 milliradians rms for a frequency range from 63 mHz to 102 kHz for pulses propagating through the SC setup. When bypassing the beam path through the SC, we find CEP fluctuations of $\Delta\Phi_{CE,bypass}$ = 250 milliradians rms. These values contain significant contributions from amplitude-to-phase conversion in our microstructure fiber-based detection setup for $\Delta\Phi_{CE}$. Hence, we do not unambiguously measure any added CEP noise intrinsic to the SC setup.
To distinguish between intrinsic SC effects and amplitude-to-phase conversion, we introduce controlled beam pointing fluctuations $\Delta\alpha$ and again compare the phase noise introduced when passing through / bypassing the SC. Our measurements do not reveal any intrinsic effects of the SC system, but allow us to place an upper limit on the sensitivity of our SC system of $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha < 13000$ rad/rad. Our results demonstrate experimentally that there is not a strong coupling mechanism between CEP and beam pointing through a stretcher/compressor , as well as measuring significantly smaller CEP fluctuations than experimental results reported previously.

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References and links

1. R. Bartels, S. Backus, E. Zeek, L. Misoguti, G. Vdovin, I. P. Christov, M. M. Murnane, and H. C. Kapteyn, "Shaped-pulse optimization of coherent emission of high-harmonic soft X-rays," Nature **406**, 164-166 (2000).
2. R. Bartels, S. Backus, I. Christov, H. Kapteyn, and M. Murnane, "Attosecond time-scale feedback control of coherent X-ray generation," Chem. Phys. **267**(1-3), 277-289 (2001).
3. I. P. Christov, M. M. Murnane, and H. C. Kapteyn, "High-Harmonic Generation of Attosecond Pulses in the "Single-Cycle" Regime," Phys. Rev. Lett. **78**, 1251-1254 (1997).
4. I. P. Christov, R. Bartels, H. C. Kapteyn, and M. M. Murnane, "Attosecond time-scale intra-atomic phase matching of high harmonic generation," Phys. Rev. Lett. **86**, 5458-5461 (2001).
5. C. G. Durfee, A. Rundquist, S. Backus, Z. Chang, C. Herne, H. C. Kapteyn, and M. M. Murnane, "Guided-wave phase-matching of ultrashort-pulse light," J. Nonlinear Opt. Phys. Mat. **8**, 211-234 (1999).
6. G. G. Paulus, F. Grasbon, H. Walther, P. Villoresi, M. Nisoli, S. Stagira, E. Priori, and S. De Silvestri, "Absolute-phase phenomena in photoionization with few-cycle laser pulses," Nature **414**, 182-184 (2001).

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7. A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. S. Yakoviev, A. Scrinzi, T. W. Hansch, and F. Krausz, "Attosecond control of electronic processes by intense light fields," Nature **421**, 611-615 (2003).
8. E. Zeek, K. Maginnis, S. Backus, U. Russek, M. Murnane, G. Mourou, H. Kapteyn, and G. Vdovin, "Pulse compression by use of deformable mirrors," Opt. Lett. **24**, 493-495 (1999).
9. E. Zeek, R. Bartels, M. M. Murnane, H. C. Kapteyn, S. Backus, and G. Vdovin, "Adaptive pulse compression for transform-limited 15-fs high- energy pulse generation," Opt. Lett. **25**, 587-589 (2000).
10. D. Jones, S. Diddams, J. Ranka, A. Stentz, R. Windeler, J. Hall, and S. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science **288** (5466), 635-639 (2000).
11. S. T. Cundiff and J. Ye, "Colloquium: Femtosecond optical frequency combs," Reviews of Modern Physics **75**(1), 325-342 (2003).
12. I. P. Christov, H. C. Kapteyn, and M. M. Murnane, "Quasi-phase matching of high-harmonics and attosecond pulses in modulated waveguides," Opt. Express **7**, 362-367 (2000). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-7-11-362
13. A. Paul, R. A. Bartels, R. Tobey, H. Green, S. Weiman, I. P. Christov, M. M. Murnane, H. C. Kapteyn, and S. Backus, "Quasi-phase-matched generation of coherent extreme-ultraviolet light," Nature **421**, 51-54 (2003).
14. R. Kienberger, E. Goulielmakis, M. Uiberacker, A. Baltuska, V. Yakovlev, F. Bammer, A. Scrinzi, T. Westerwalbesloh, U. Kleineberg, U. Heinzmann, M. Drescher, and F. Krausz, "Atomic transient recorder," Nature **427**, 817-821 (2004).
15. D. Strickland and G. Mourou, "Compression of Amplified Chirped Optical Pulses," Opt. Commun. **56**, 219-221 (1985).
16. J. Seres, A. Mueller, E. Seres, K. O'Keeffe, and M. Lenner, R. F. Herzog, and D. Kaplan, C. Spielmann, F. Krausz, "Sub-10-fs, terawatt-scale Ti:sapphire laser system," Opt. Lett. **28**, 1832-1834 (2003).
17. F. W. Helbing, G. Steinmeyer, J. Stenger, H. R. Telle, and U. Keller, "Carrier-envelope-offset dynamics and stabilization of femtosecond pulses," Appl. Phys. B **74**, S35-S42 (2002).
18. M. Kakehata, H. Takada, Y. Kobayashi, K. Torizuka, H. Takamiya, K. Nishijima, T. Homma, H. Takahashi, K. Okubo, S. Nakamura, and Y. Koyamada, "Carrier-envelope-phase stabilized chirped-pulse amplification system scalable to higher pulse energies," Opt. Express **12**, 2070-2080 (2004). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-10-2070
19. H. Wang, S. Backus, Z. Chang, R. Wagner, K. Kim, X. Wang, D. Umstadter, T. Lei, M. Murnane, and H. Kapteyn, "Generation of 10-W average-power, 40-TW peak-power, 24-fs pulses from a Ti : sapphire amplifier system," J. Opt. Soc. Am. B **16**, 1790-1794 (1999).
20. T. M. Fortier, J. Ye, S. T. Cundiff, and R. S. Windeler, "Nonlinear phase noise generated in air-silica microstructure fiber and its effect on carrier-envelope phase," Opt. Lett. **27**, 445-447 (2002).
21. S. Witte, R. T. Zinkstock, W. Hogervorst, and K.S.E.Eikema, "Control and precise measurement of carrier-envelope phase dynamics," Appl. Phys. B **78**, 5-12 (2004).

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1. Introduction

Amplification of carrier-envelope phase (CEP) stabilized femtosecond (fs) laser pulses has recently received considerable interest. One major reason is that extreme nonlinear processes such as HHG driven by amplified laser pulses, exhibit a strong dependence on the driving laser field,[1-4] and are therefore sensitive to the CEP of the driving laser pulses [5-7].

Combination of pulse shaping techniques[8, 9] with methods of CEP control, [10, 11] offers the possibility of controlling the complete electric field of the ultrafast pulse in the time-domain, with attosecond precision. This allows us to access the fastest time-scales to date that are possible with modern laser technology. It has thus become possible to manipulate electron dynamics with attosecond precision,[1, 2, 4] to manipulate phase-matching of the HHG process,[12, 13] and to generate pulses of light with sub-femtosecond duration [14].

Chirped pulse amplification (CPA)[15] is the most widespread technique for amplification of fs pulses. In this scheme the pulse is stretched before amplification by introducing a positive chirp, and afterwards recompressed by compensating for the positive chirp introduced in the stretcher and gain material with an equally large negative chirp. Amplified CEP stabilized pulses were first produced using stretchers based on material dispersion followed by compression by prism compressors [7]. These systems reach pulse energies of ~3 millijoules, limited by the required amount of stretching and recompression [16].

These limitations could be overcome by CPA using grating based stretcher / compressor systems. Such systems however, have been predicted to have a more severe effect on CEP

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stability than material-based stretcher compressor systems, due to a stronger coupling of beam pointing fluctuations to CEP fluctuations [17].

In this work, we quantitatively investigate the effect of a grating based stretcher compressor setup on CEP stability. We employ two self-referencing setups [11] to detect the root mean square (rms) CEP fluctuations both in the oscillator stabilization loop ($\Delta\Phi_{CE}$) and out of loop ($\Delta\Phi_{CE}'$), as shown in Fig. 1. The difference $\Delta\Phi_{CE,SC} := \Delta\Phi_{CE} - \Delta\Phi_{CE}'$ is a direct measure of CEP fluctuations introduced outside the oscillator stabilization loop, in the beam path through the stretcher-compressor. We perform the measurement both with pulses that have passed the SC setup ($\Delta\Phi_{CE,SC}$), as well as with pulses that bypass the stretcher compressor ($\Delta\Phi_{CE,bypass}$).

Our results, presented below, show quantitatively that the coupling between beam pointing and CEP introduced in our grating based SC setup is sufficiently small to enable phase stabilized amplification using a standard stretcher / compressor CPA system.

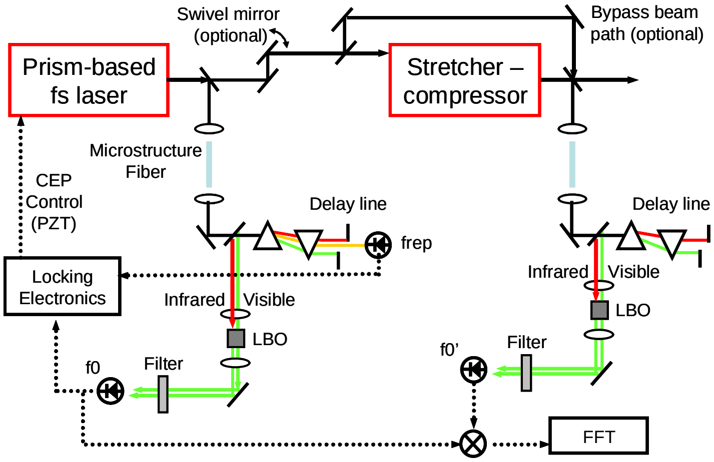

Fig. 1. The setup consists of a prism-based fs laser coupled into a grating-based stretcher-compressor (SC). Two microstructure-based setups measure the offset frequency of the phase-locked laser spectra, after the oscillator (in-loop, f_0) and after the SC (out of loop, f_0'). These are converted into phase fluctuations using Eq.1. The difference between CEP fluctuations introduced inside and outside the oscillator stabilization loop are measured by mixing f_0-f_0', and FFT analyzed. Optionally the beam bypasses the SC. A swivel mirror before the SC allows introduction of controlled beam pointing fluctuations.

This work adds to recent results reported by Kakehata *et al*.[18] that show CEP stability of oscillator pulses can be retained after amplification to 3.5 mJ using a regenerative plus multipass amplifier system, together with a grating-based stretcher-compressor. Their measurement of CEP changes introduced by beam pointing fluctuations did not separate the effects of CEP fluctuations in the stretcher and compressor from additional CEP fluctuations in the regenerative amplifier and amplifier ring, as well as amplitude-to-phase conversion in the CEP detection setup (using a Krypton gas filled hollow fiber for spectral broadening).

Furthermore, in that work it is difficult to distinguish between CEP changes and pulse timing fluctuations, due to the spectral interferometry technique that was used over a limited wavelength range.

Our measurements are based on a different CEP detection method that does not introduce an ambiguity between CEP changes and timing fluctuations. We also take into account amplitude-to-phase conversion in our CEP detection setup by comparing measurements of pulses propagating through, as well as bypassing, the SC setup**.** Our measurements therefore extend and clarify the results of Ref. [18]. Finally, we demonstrate experimentally that there is not a strong coupling mechanism between CEP and beam pointing through a

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stretcher/compressor, as well as measuring significantly smaller CEP fluctuations than experimental results reported previously.

2. Setup and measurement methods

Our setup is shown in Fig. 1. It consists of a CEP stabilized prism-based Ti:Sapphire oscillator producing pulses of ~ 25 fs duration, with a repetition rate of f_{rep} = 96 MHz and a spectrum centered at 820 nm, with an average power of 850 mW. For CEP detection we use a self referencing setup using a 4.5 cm long air-silica microstructure fiber to broaden the spectrum to an octave. This setup allows direct measurement of the offset frequency f_0 of the mode-locked spectrum. The offset frequency f_0 is related to the pulse-to-pulse CEP slip $\Delta\Phi_{CE}$ by -

$$\frac{f_0}{f_{rep}} = \frac{\Delta\Phi_{CE}}{2\pi} \tag{1}$$

The repetition rate f_{rep} is detected on a separate photodiode. We stabilize $f_0 / f_{rep} = p/q$ to 3/8. The ratio p/q = 3/8 ensures that every 8th pulse experiences a $3{*}2\pi$ phase slip and is therefore indistinguishable from the 1st pulse. Practically, CEP stabilization is achieved using a piezoelectric tilt mirror, achieving a loop bandwidth around 10 kHz. The measured rms in-loop phase fluctuations are 400 milliradians (integrated from 63 mHz to 102 kHz).

Pulses from this oscillator are then sent through a grating based stretcher in a double pass configuration. It consists of a grating (1200 grooves/mm) and a curved imaging mirror of 406 mm focal length. The stretched pulse duration, at 220 picoseconds, is suitable for amplification up to Joule or higher pulse energy level [19]. Pulse recompression to ~ 35 fs is achieved using a 1200 grooves/mm grating pair in double pass configuration.

Measurement of the offset frequency f_0’ of the recompressed pulses is performed using a second self-referencing setup similar to the first one. From the measurement of f_0’, the phase noise $\Delta\Phi_{CE}$’ is determined from Eq. (1). In order to measure the fluctuations of CEP introduced outside the oscillator stabilization loop, i.e., $\Delta\Phi_{CE,SC} := \Delta\Phi_{CE} - \Delta\Phi_{CE}'$, we mix the f_0 and f_0’ photodiode signals to an output signal around DC. The mixer output voltage is $V_{mixer} \sim \mathrm{Cos}(\Delta\Phi_{CE,SC} + \phi)$, where ϕ is an arbitrary phase offset. For suitable ϕ and small $\Delta\Phi_{CE,SC}$, $V_{mixer} \sim \Delta\Phi_{CE,SC}$ is proportional to the phase difference to be measured. We take care that the fluctuations $\Delta\Phi_{CE,SC}$ are not larger than ~ $\pi/5$ so that the mixer output is a true representation of the phase noise $\Delta\Phi_{CE,SC}$. The signal is analyzed on an FFT signal analyzer (62.5 mHz to 102.4 kHz range). For each frequency range we take an average over four data sets. The FFT signal V_{rms}^2/Hz is converted to the CEP power spectral density (PSD) $\Delta\Phi_{CE,SC,rms}^2$/Hz using the mixer output peak-to-peak voltage corresponding to $\Delta\Phi_{CE,SC} = \pi$.

The phase noise $\Delta\Phi_{CE,SC}$ is obtained from the power spectral density by integrating from the upper frequency f_u to the lower limit f_l of the FFT frequency range -

$$\Delta\Phi_{CE,SC} = \sqrt{2\int_{f_u}^{f_l} \Delta\Phi^2_{CE,SC,rms} \big/ Hz \, df} \tag{2}$$

3. Results and discussion

Figure 2(a) shows the measured power spectral density of phase fluctuations, $\Delta\Phi_{CE,SC,rms}^2$/Hz (red curve), as well as the RMS phase fluctuations $\Delta\Phi_{CE,SC}$ (black curve) introduced when the pulses propagate through the stretcher compressor. The RMS phase fluctuations $\Delta\Phi_{CE,SC}$ are obtained from the PSD using Eq. (2). Figure 2(b) shows the corresponding data measured when the pulses bypass the stretcher compressor.

For pulses passing through the stretcher compressor, we measure $\Delta\Phi_{CE,SC}$ = 340 milliradians of CEP fluctuations, whereas we measure $\Delta\Phi_{CE,bypass}$ = 250 milliradians for pulses

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bypassing the stretcher-compressor. Both values are dominated by the effects of mechanical resonances of optical components in the frequency range from 100 Hz to 600 Hz.

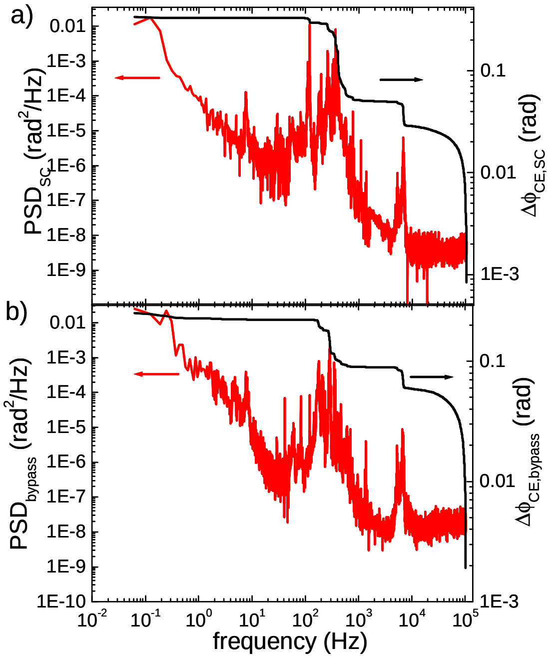

Fig. 2. Comparison in CEP fluctuations a) passing through the SC, b) bypassing the SC.

We expect that the CEP fluctuations $\Delta\Phi_{CE,bypass}$ of the bypassed beam would be dominated by nonlinear amplitude-to-phase conversion in the detection setup for $\Delta\Phi_{CE}$' [20, 21]. The slightly larger value of $\Delta\Phi_{CE,SC} = 340$ millirad when passing through the stretcher-compressor, may either be caused by additional CEP fluctuations introduced by stretcher-compressor, but may also be due to slight differences in alignment, lock settings or differing optical mounts and beam paths. The close similarity of the values $\Delta\Phi_{CE,SC}$ and $\Delta\Phi_{CE,bypass}$ therefore does not permit a precise determination of effects intrinsic to the stretcher-compressor. We have measured the RMS beam pointing fluctuations of the laser beam into the SC setup to be $\Delta\alpha_{rms} < 0.1$ microradians, assuming the beam fluctuations to originate from the oscillator Ti:sapphire crystal. We note that this allows us to only set a relatively large upper bound of beam pointing sensitivity of the SC setup, $\Delta\Phi_{CE,SC} / \Delta\alpha_{rms} < 3.4\ 10^6$ rad/rad, likely dominated by effects not intrinsic to the SC.

In order to obtain a clearer signature of CEP effects occurring in the stretcher-compressor setup, we artificially introduce a beam pointing oscillation of controlled amplitude. We use a swivel mirror in front of the stretcher compressor, at a distance of ~ 90 cm to the first grating. We again analyze the introduced phase fluctuations $\Delta\Phi_{CE,SC}$ on a FFT signal analyzer. In this way we can separate the spectral component at the swivel frequency 50 Hz from all other CEP fluctuations.

As the beam pointing oscillations inevitably cause amplitude to phase coupling in the second self-referencing setup, we have performed the measurement both for a beam propagating through the SC, and for a beam bypassing it with a similar path length to the second microstructure fiber.

Figure 3 shows the results of this measurement through the stretcher compressor. Fig. 3(a) shows the measured CE phase fluctuations $\Delta\Phi_{CE,SC}$ vs. the beam pointing angle $\Delta\alpha$, defined as the peak-to-peak angle of beam deviations. The data show a clear linear dependence with a

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slope of $\Delta\Phi_{CE,SC}$ / $\Delta\alpha$ = 3.9 (+/- 0.1) 10^4 rad/rad. As we show, below this value is dominated by amplitude-to-phase coupling in the second self-referencing setup. The beam pointing angle is typically limited to $\Delta\alpha$ ~ 17 microradians in order to keep fluctuations $\Delta\Phi_{CE}$ smaller ~ π/5. In Fig. 3(b) we plot the simultaneously measured rms power fluctuations $\Delta P_{rms} = \Delta P_{pp}/(2\sqrt{2})$, where ΔP_{pp} are the peak-to-peak power fluctuations detected after the second microstructured fiber. Figure 3(c) shows $\Delta\Phi_{CE,SC}$ / ΔP_{rms}, where only the power fluctuations due to swiveling are used, i.e., the offset of the linear fit of ΔP_{rms} vs. $\Delta\alpha$ has been subtracted from ΔP_{rms} (this offset results from steady-state beam fluctuations not related to the artificially-induced swiveling). We obtain a value of $\Delta\Phi_{CE,SC}$ / ΔP_{rms} = 2170 +/- 180 rad/W, where the error is the standard deviation of the data points.

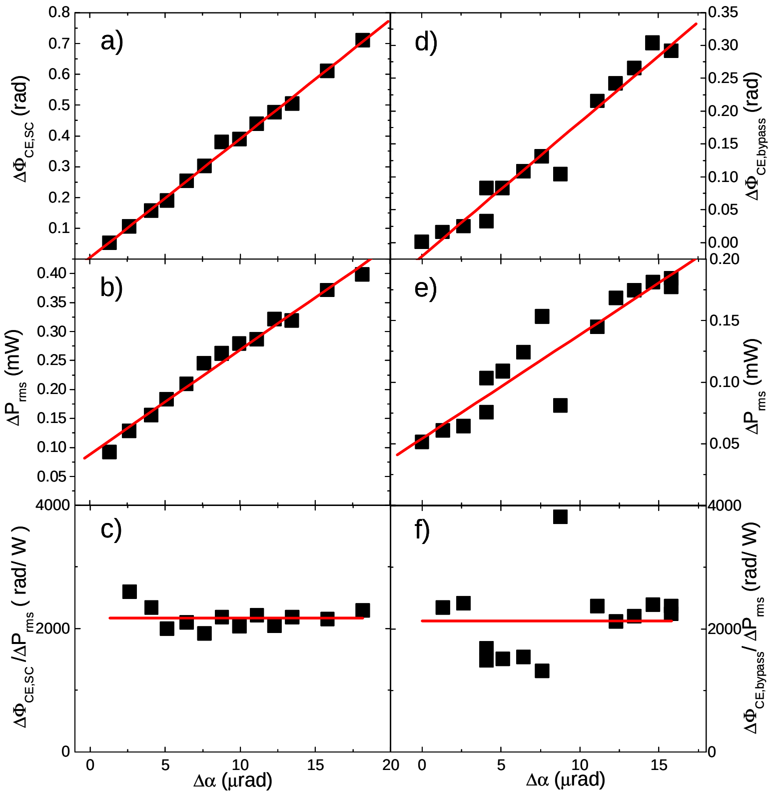

Fig. 3. Measurements of carrier-envelope phase-fluctuations $\Delta\Phi_{CE}$, power fluctuations ΔP_{rms} and the ratio of both, when beam pointing fluctuations $\Delta\alpha$ are introduced.(a-c): data for stretcher-compressor, (d-f): data for bypassing beam.

The data bypassing the stretcher-compressor are shown in Figs. 3(d-f). Again a linear dependence of ΔP_{rms} and $\Delta\Phi_{CE,bypass}$ on $\Delta\alpha$ is seen, and again we take the ratio $\Delta\Phi_{CE,bypass}/\Delta P_{rms}$. We expect this value to be equal to the amplitude-to-phase conversion coefficient Cap, and obtain $\Delta\Phi_{CE,bypass}$/ ΔP_{rms} = 2130 +/- 630 rad/W, in approximate agreement with Refs. [20, 21].

Comparing our data obtained by going through the SC and bypassing it, we see that the ratio $\Delta\Phi_{CE}$ / ΔP_{rms} is identical in both measurements, and we conclude that intrinsic fluctuations due to the SC are not contributing significantly to $\Delta\Phi_{CE,SC}$. From our data, we can

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place an upper limit on the intrinsic CE phase fluctuations introduced by the stretcher compressor $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha < 13000$ rad/rad.

We obtain this value by taking the difference $\Delta\Phi_{CEintrinsic,SC} / \Delta P_{rms} = \Delta\Phi_{CE,SC} / \Delta P_{rms} - \Delta\Phi_{CE,bypass} / \Delta P_{rms} = 40$ +/- 660 rad/W. We convert to $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha$ by writing $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha = \Delta\Phi_{CEintrinsic,SC} / \Delta P_{rms} * \Delta P_{rms} / \Delta\alpha$, and take $\Delta P_{rms} / \Delta\alpha = 18.0$ (+/- 0.7) W / rad from the slope in Fig. 3 (b). This yields $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha = 740$ +/– 12000 rad / rad, i.e. <13000 rad / rad.

Comparing this to [18] we find our upper limit for the intrinsic CE phase fluctuations introduced by the stretcher compressor to be 2.3 times smaller. The difference is likely due to amplitude-to-phase noise conversion in the hollow fiber and some ambiguity due to contributions from delay changes in the spectral interferometry setup. Contributions due to the amplification process itself are common to all configurations of CPA systems, and have proven to be sufficiently small as to not preclude CEP stabilization [7, 18].

4. Conclusions

We have carefully measured CEP fluctuations introduced by grating-based stretcher compressor systems for amplifiers using a standard design of chirped pulse amplification. From our error analysis, we find a very small upper limit on $\Delta\Phi_{CEintrinsic,SC} / \Delta\alpha = 13000$ rad/rad for our set-up. From our measured steady-state beam pointing fluctuations of $\Delta\alpha_{rms} < 0.1$ μrad, we would expect intrinsic CEP fluctuations $\Delta\Phi_{CEintrinsic,SC} < 3.6$ milliradians. Our results confirm and improve upon the conclusion of Kakehata [18] that grating based CPA systems are not a severely limiting factor for amplification of high power CEP stabilized pulses. Since our measured noise is >2x smaller than past results, there is considerable future room for improvement. Finally, we also verified experimentally for the first time that there is no severe coupling mechanism between beam pointing in a stretcher/compressor and the CEP.

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