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Power locking of high-repetition-rate chirped pulse amplifiers

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ABSTRACT We report a feedback control scheme that minimizes the energy fluctuations of high power femtosecond pulses from a 1 kHz laser amplifier. The pulse energy variation in the frequency bandwidth 0–500 Hz was obtained by a photodiode and a low pass filter. The measured signal was fed to a proportional-integral-derivative (differential) (PID) controller that changed the amplitude of the high voltage pulses applied to a Pockels cell. The variation of average power was reduced from 1.33% RMS to 0.28% RMS, which improved the carrier-envelope phase stability from 500 mrad to 200 mrad as measured by two f-to-$2f$ interferometers. The long term stability of the laser was kept to approximately 0.5% RMS.

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1 Introduction

Recently the rapid development of the ultrafast laser has drawn much attention in various areas because of its ultrashort pulse duration, high peak intensity, and broad spectra [1]. One important parameter for characterizing laser performance is the pulse to pulse energy stability, which is important not only in nonlinear laser-atom interations [2], but also in femtosecond laser micro/nano machining [3]. Of particular interest, with the advent of few-cycle pulse generation is the effect of power stability on carrier-envelope (CE) phase stabilization [4, 5]. In such a system, the few-cycle pulses are generated from chirped pulse amplifiers (CPA) followed by nonlinear pulse compression, and their CE phase is stabilized by locking the CE offset frequency of the oscillator [6, 7] as well as compensating the slow phase drift in the amplifier [8]. The latter was done by measuring the CE phase variation with an f-to-$2f$ interferometer and by using the measured result as a feedback control signal [9]. The stability of the CE phase relies on the accuracy of the CE phase measurement, which is sensitive to laser power fluctuations [2].

In the f-to-$2f$ interferometer, the amplified laser pulses are focused into a sapphire plate to form a single filament, which broadens the pulse spectrum to cover an octave [10]. The CE phase of the laser, φ_{CE}, affects the spectral interference between the component in the pulse with wavelength centered around 500 nm and the frequency doubled component originally centered at 1000 nm of the white light emitted by the filament. The total spectral phase retrieved from the f-to-$2f$ interferogram can be expressed as

$$\Phi(\omega) = \varphi_{WL}(\omega) - \varphi_{SHG}(\omega) + \omega\tau_0 + (\varphi_{CE} + \delta\varphi_{CE}) , \quad (1)$$

where $\varphi_{WL}(\omega)$ and $\varphi_{SHG}(\omega)$ are the spectral phase of the 500 nm pulse and the frequency doubled pulse respectively, τ_0 is the time delay between these two components, and $\delta\varphi_{CE}$ is the CE phase change due to self-steepening [11]. In fact, it is the total phase $\Phi(\omega)$ that is being stabilized. Except for φ_{CE}, the other four terms of the total phase are influenced by laser intensity fluctuations inside the interferometer [2, 12]. Therefore, it is clear that good laser power stability is required for stabilizing the CE phase through stabilizing the total phase $\Phi(\omega)$.

2 Previous schemes

Under well-controlled environmental conditions (temperature 20 °C ± 5 °C and relative humidity 50% ± 5%) and after several hours of warming up, the laser energy fluctuation of typical diode pumped kilohertz femtosecond laser systems is 1.5% RMS [13]. The long term energy drift is also close to this value [13]. Our amplifier is pumped by two Nd:YLF lasers that are diode pumped (Evolution 30 from Coherent Inc). The power fluctuation of this kind of laser is also on the order of 1%. Even when the amplifier is operated in the near-saturation regime, the output power stability is not better than the pump laser. Improving the power stability of the pump laser using the feedback technique or other method may improve the amplifier output stability. In a time scale of minutes to hours, the thermal drift of the seed beam and pump pointing may affect their overlap in the gain medium. This effect can be reduced by improving the stability of the temperature and humidity of the air in the laser room. Previously, a stabilization scheme making use of a photoconductive switch to drive a Pockels cell discharge was introduced [14]. Although the energy fluctuation was suppressed from 7% to 0.64%, 50% of the total energy was lost during the stabilization process. Moreover, since the added Pockels cell was located after the amplifier, the high power pulses could cause nonlinear effects

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or even damage the device. For regenerative amplifiers, the laser energy can be stabilized by controlling the gain saturation conditions [15]. However, the pulse duration of the laser systems that demonstrated this technique was 110 fs, which is difficult to use for generating few-cycle pulses. We reported a method to improve the laser power stability of multi-pass amplifiers by using the Pockels cell located between the oscillator and chirped pulse amplification (CPA) system. It is easier to produce shorter pulses from multi-pass amplifiers because the dispersion and gain narrowing effect is much less as compared to that of regenerative amplifiers.

3 Experimental setup

The new power locking scheme was tested with the Kansas light source laser system as shown in Fig. 1 [16]. The laser pulses from a CE phase stabilized oscillator, with a 77 MHz repetition rate(Femtolasers, Femtosource Scientific), were selected by the Pockels cell to be stretched, amplified and compressed. These laser pulses are amplified in a single stage multi-pass amplifier. The first seven passes have high gain, but low efficiency. They pre-amplify the pulses from the few nJ regime to a few μJ. The second seven passes have low gain, but high efficiency, and complete the amplification to the mJ level. The final output after the compressor is 2 mJ, with 30 fs pulse duration. The Pockels cell that originally served as a pulse picker was also used as a power modulator in this work. The in-loop powermeter (Newport 1935) using a Si photodiode as the power probe was positioned in the beam path of the zero order diffraction from a compressor grating. There, the measured average power was proportional to the total output laser power. The analog output of the powermeter was the 1 kHz electronic pulse train from the Si photodiode amplified by the built-in amplifiers of the powermeter. The signal representing the fluctuation of the laser pulse energy was extracted by an external low pass analog filter applied after the powermeter. Then this signal is sent to a proportional-integral-derivative (differential) (PID) controller (SRS SIM960), which changed the high voltage pulses applied to the Pockels cell to control its transmittance. In order to reduce the noise originating from the pump lasers and room light, a 800 nm narrow band pass filter with full width half maximum 40 nm was placed in front of the powermeter's detector.

4 Result and discussion

The Pockels cell behaves like a voltage controlled wave plate. Without power stabilization, the amplitude of the 1 kHz high voltage pulses applied to the Pockels cells was constant, and usually was set at the half-wave voltage $V_{\lambda/2} \approx 7$ kV, which generated a 1 kHz laser pulse train. In order to choose an appropriate working voltage range for the Pockels cell to compensate the laser power fluctuation, the relation between the voltage applied on the Pockels cell and the laser output power after the compressor was measured, as shown in Fig. 2. By comparing the transmission curve of the Pockels cell in Fig. 2, it was concluded that the amplifier worked in the saturation regime. Usually, operating an amplifier close to saturation maximized the output energy and reduced the susceptibility to fluctuations of the pump and seed pulses. In this scheme, to have enough range for feedback control, the Pockels cell was set to work around 5000 V, which reduced the output power by 10%. Thus, the pulse to amplified spontaneous emission (ASE) ratio was changed only by 10%. Pre-pulses and post-pulses due to reflections scaled with the main pulses. The pulse contrast was not affected much by introducing the feedback. At this setting, 10% voltage adjustments could compensate for 3% laser power fluctuation. Power spectral density measurement showed that the analog signal of the in-loop powermeter contained fast jitter and slow drift without power locking. By optimizing the PID controller parameters and setting 500 Hz as the cutoff frequency of the low pass filter, we suppressed the power noise below 40 Hz as evidenced in Fig. 3. In the time domain, the power fluctuation was 1.33% RMS without power locking, like most kilohertz

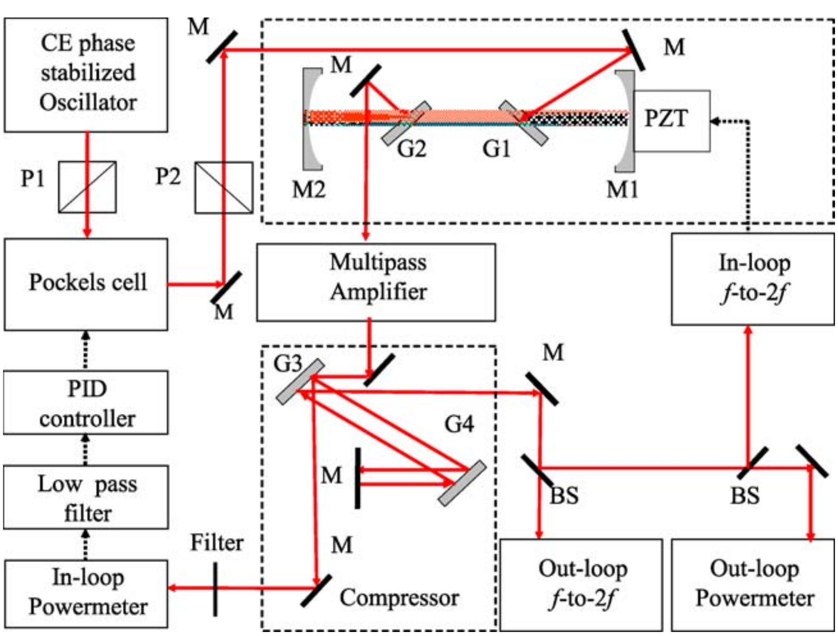

FIGURE 1 The Kansas light source (KLS) laser intensity stabilization system. The in-loop powermeter was put in the path of the zero order diffraction beam and sent the power signal to the PID controller. By using feedback control, the PID varied the voltage applied on the Pockels cell, which in turn changed the polarization of the output from the oscillator and stabilized the laser intensity. *Red arrows* are the laser paths and *dashed arrows* represent electronic circuits

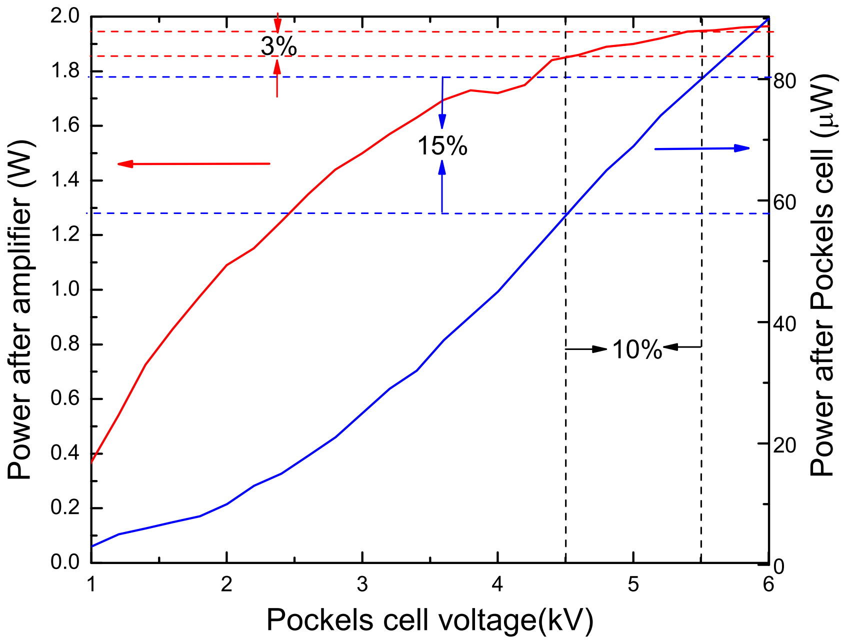

FIGURE 2 The output power vs. Pockels cell voltage. The horizontal axis was the voltage applied on the Pockels cell, and the vertical axis was the power measured after Pockels cell and amplifier respectively

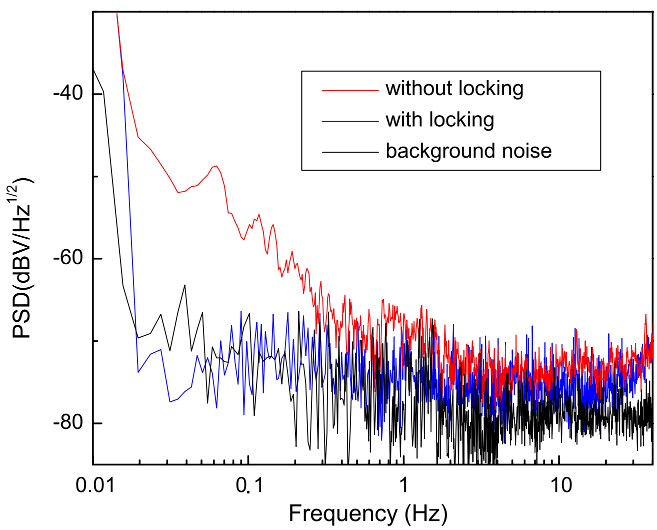

FIGURE 3 The power spectral density of the analog signal coming out of the powermeter. After locking the power, the low frequency (below 40 Hz) noise was suppressed

Ti:sapphire CPA lasers. As shown in Fig. 4, the fluctuation of the out-loop power dropped to 0.28% RMS when the feedback control was turned on, which showed the effectiveness of this scheme. To further prove the success of this method, long term stability data were also measured by using the out-loop powermeter as shown in Fig. 5, which indicated the RMS power fluctuation 0.3%.

During the power stabilization process, the voltage on the Pockels cell changed from pulse to pulse. To produce CE phase stabilized pulses, it was important that the voltage change did not introduce significant CE phase variation between pulses. By applying the electric field, the ordinary index of refraction n_0 of the crystal inside the Pockels cell in the x and y directions was changed to $n_x = n_0 + \Delta n/2$ and $n_y = n_0 - \Delta n/2$. Here, $\Delta n = n_0^3 r_{63} V/L$, $r_{63} \approx 23.3 \times 10^{-12}$ m/V for $KD*P$ crystal, V was the voltage applied and L was the crystal length. It was assumed that incident laser was polarized 45° from both the x and y directions, which can be described as

$$\boldsymbol{E}_i(t) = \frac{\sqrt{2}}{2} E_{0i}(t)(\hat{i} + \hat{j})\mathrm{e}^{\mathrm{i}\omega t} . \tag{2}$$

where E_{0i} is the amplitude of electric field; $\hat{i}$ and $\hat{j}$ are the unit vectors of x and y direction, respectively. At the exit of the crystal, the field was

$$\boldsymbol{E}_\mathrm{e}(t) = \frac{\sqrt{2}}{2} \left[\hat{i} E_{0i} \left(t - \frac{L}{v_{gx}} \right) \mathrm{e}^{\mathrm{i}\left(\omega\left(t - \frac{L}{v_{px}}\right)\right)} + \hat{j} E_{0i} \left(t - \frac{L}{v_{gy}} \right) \mathrm{e}^{\mathrm{i}\left(\omega\left(t - \frac{L}{v_{py}}\right)\right)} \right] , \tag{3}$$

where v_{gx} and v_{gy} are the group velocities, and v_{px} and v_{py} are the phase velocities in the x and y directions respectively. To simplify the analysis, it was assumed that $v_{gx} = v_{gy} = v_g$, which can be justified by the fact that the dispersion in the two directions was almost identical. In the moving frame $t' = t - L/v_g$, the field can be expressed as

$$\boldsymbol{E}_\mathrm{e}(t') = \frac{\sqrt{2}}{2} E_{0i}(t') \times \left[\hat{i}\mathrm{e}^{\mathrm{i}\frac{\omega}{c}L(n_g - n_x)} + \hat{j}\mathrm{e}^{\mathrm{i}\frac{\omega}{c}L(n_g - n_y)} \right] \mathrm{e}^{\mathrm{i}\omega t'} , \tag{4}$$

The field passing the second polarizer was

$$\begin{aligned} E(t') &= \frac{1}{2} E_{0i}(t') \left[\mathrm{e}^{\mathrm{i}\frac{\omega}{c}L(n_g - n_x)} + \mathrm{e}^{\mathrm{i}\frac{\omega}{c}L(n_g - n_y)} \right] \mathrm{e}^{\mathrm{i}\omega t'} \\ &= \frac{1}{2} E_{0i}(t') \left[\mathrm{e}^{-\mathrm{i}k_0 \Delta n L/2} + \mathrm{e}^{\mathrm{i}k_0 \Delta n L/2} \right] \mathrm{e}^{\mathrm{i}\omega t' + k_0(n_g - n_0)} \\ &= E_{0i}(t') \sin(k_0 \Delta n L/2) \mathrm{e}^{-\mathrm{i}[\omega t' + \Delta\varphi_\mathrm{CE}]} . \end{aligned} \tag{5}$$

Therefore, when $v_{gx} = v_{gy} = v_g$, then the CE phase change, $\Delta\varphi_\mathrm{CE}$, was the same in the x and y directions and was independent of the voltage applied on the Pockels cell. When the difference in v_{gx} and v_{gy} was taken into account, the CE phase changes in the two directions were the following:

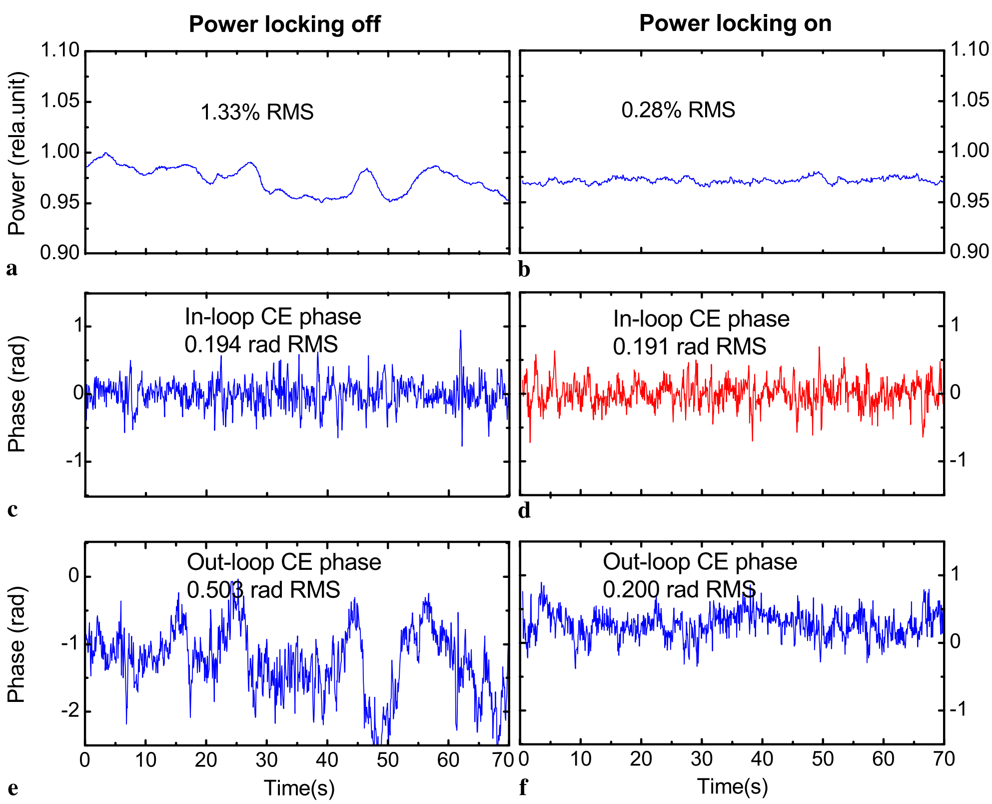

FIGURE 4 The *left column* and *right column* were the measurement of laser power and CE phase stability with and without power locking. (**a**) and (**b**) show normalized power. After stabilization the power fluctuation had decreased to one fifth of its usual value; (**c**) and (**d**) are in-loop CE phase; (**e**) and (**f**) are out-loop CE phase

$$\Delta\varphi_{\mathrm{CE},x} = \omega_c \left(\frac{1}{v_{gx}} - \frac{1}{v_{px}}\right) L = \Delta\varphi_{\mathrm{CE}} - \frac{\mathrm{d}\,\Delta n}{2\,\mathrm{d}\lambda} 2\pi L\,, \qquad (6)$$

$$\Delta\varphi_{\mathrm{CE},y} = \omega_c \left(\frac{1}{v_{gy}} - \frac{1}{v_{py}}\right) L = \Delta\varphi_{\mathrm{CE}} + \frac{\mathrm{d}\,\Delta n}{2\,\mathrm{d}\lambda} 2\pi L\,. \qquad (7)$$

The CE phase difference in the two directions was the following:

$$\begin{aligned}\delta\varphi_{\mathrm{CE}} &= \pi L \frac{\mathrm{d}\,\Delta n}{\mathrm{d}\lambda} \\ &= \frac{3}{n_0}\left(n_0^3 r_{63} \frac{V_{\lambda/2}}{L}\right) \frac{V}{V_{\lambda/2}} \left(\frac{\mathrm{d}n_0}{\mathrm{d}\lambda} 2\pi L\right) \\ &= \frac{3\lambda V \Delta\varphi_{\mathrm{CE}}}{2 n_0 V_{\lambda/2} L}\,, \qquad (8)\end{aligned}$$

where $\Delta\varphi_{\mathrm{CE}}$ was the CE phase shift without applying the voltage. For $KD*P$, $\Delta\varphi_{\mathrm{CE}}/L = 2\pi/40\,\mu\mathrm{m}$. If $\Delta V/V_{\lambda/2} \le 10\%$, $\delta\varphi_{\mathrm{CE}}$ will change less than 10 mrad, which was much smaller than 150 mrad, and was the typical RMS fluctuation of the stabilized CE phase.

In order to investigate the effect of power stabilization on the CE phase locking, besides the in-loop f-to-$2f$ interferometer used to control the grating separation in the stretcher for the slow CE phase drift [8, 17], an out-loop f-to-$2f$ interferometer was used to check the phase stability. The in-loop and out-loop CE phases were measured concurrently with and without power locking. As shown in Fig. 4, without power locking, the difference of the in-loop and out-loop standard deviation was 309 mrad. After locking the power, their difference dropped dramatically to 9 mrad, which proved that the reduction of the power fluctuation could significantly improve CE phase stability. The correlation between power change and the out-loop CE phase shift can be seen by comparing Fig. 4a and e. The result can be understood by using (1). Since the white-light generation and second harmonic generation processes in the two f-to-$2f$ interferometers were not identical, the CE phase measured by the two interferometers had different power dependencies [2]. Quantitatively, the effect of power fluctuation on the CE phase measurement could be determined by modulating the input power of the in-loop f-to-$2f$ interferometer and measuring the CE phase from the out-loop f-to-$2f$ interferometer with the power stabilized [4].

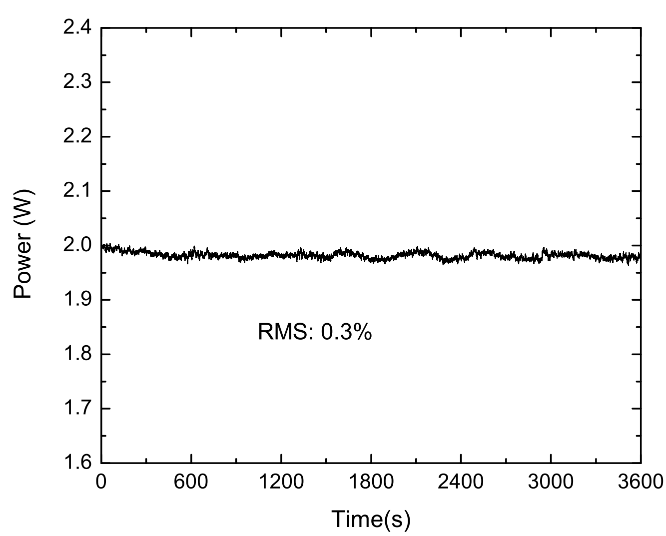

FIGURE 5 The long term stability of the laser output measured by a thermal powermeter

5 Conclusion

In conclusion, it was demonstrated that the laser power fluctuation could be reduced significantly from 1.33% to 0.28% RMS by feedback controlling the voltage applied on the Pockels cell, which reduced the out-loop CE phase noise from 500 mrad to 200 mrad RMS. This scheme utilized the Pockels cell that is already in the CPA system, which did not introduce extra optical material dispersion. The power loss was less than 10%, which is much smaller than the previous scheme (50%) [14]. Also the Pockels cell was located before the power amplifier, which introduced a very small nonlinear effect. Since strong laser field-atom interactions are intrinsically nonlinear, even for experiments without CE phase stabilization, the power stabilization demonstrated here is also useful. This work was supported by U.S. Department of Energy and by the National Science Foundation.

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