Development of a Pointing and Power Stabilization System for Intense Few-cycle Lasers

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We have developed and demonstrated a pointing and power stabilization system for intense few-cycle pulse generation at high repetition rates. The output power from a 1 kHz Ti:sapphire laser system was controlled by the voltage applied to a Pockels cell, and the beam pointing was controlled by a fast analog device composed of a position-sensitive detector and a piezo-driven mirror. As a result, the pointing and power fluctuations were stabilized within 1 µm rms and 0.15% rms, respectively, by feedback control. After spectral broadening inside a hollow fiber for pulse compression, the fluctuations in the output power and spectral intensity were 1.1% rms and 3.5% rms, respectively. Finally, we obtained stable intense few-cycle pulses with an energy of 2.7 mJ and a pulse duration of 5.4 fs.

Key Words: Laser stabilization, Spectral broadening, Pulse compression, Ultrashort pulses

1. Introduction

Recently, intense ultrashort pulse generation with a pulse duration corresponding to few-optical cycles has been widely investigated. The stability of laser beam pointing and that of the output power are very important parameters in practical applications. For instance, in hollow-fiber pulse compression for few-cycle pulse generation, pointing fluctuations can cause damage to the fiber input face, and both the power and pointing fluctuations can induce shot-to-shot variation of the compressed power and nonlinear spectral broadening. Furthermore, these fluctuations degrade carrier-envelope (CE) phase locking in ultrafast laser systems based on chirped-pulse amplification.2) The main cause of power fluctuation originates from pump power fluctuations in chirped-pulse amplification (CPA) systems. Power fluctuation can be improved by feedback control or a self-stabilization technique.2,3) Meanwhile, beam pointing fluctuations are caused by thermal expansion and contraction of support structures, air turbulence and vibration.

![Diagram](image-url)

Fig.1 Schematic of the experimental setup for beam pointing and power stabilization. PC: personal computer, PID: proportional-integral-derivative controller, BS: beam splitter, PSD: position-sensitive detector, PM: power meter, NDF: neutral density filter, CM: chirped mirror. PM #1 is used for power stabilization of the 1 kHz laser system. PM #2 is used for monitoring the power stability outside the feedback loop. The PSD is used for feedback control. The spectrum, broadened by self-phase modulation in the fiber, was monitored with a spectrometer. The compressed pulse duration was measured with SPIDER after dispersion compensation with the CM.
of optical benches. So far, several investigations on the pointing stabilization of ultrafast laser systems have been demonstrated using feedback control with a charge coupled device (CCD) as a position sensor, a personal computer as a digital signal processor and an active mirror with electric actuators. However, this cannot stabilize the short-term component in pointing fluctuations. On the other hand, both long-term and short-term fluctuations can be eliminated by using analog feedback control with a two-dimensional position-sensitive detector (PSD) and a proportional-integral-derivative (PID) controller because they are fast enough to monitor short-term fluctuations. In our recent work, we developed and demonstrated a beam pointing stabilization system that can stabilize both slow and fast fluctuations and eliminate fluctuations in both the output power and spectral broadening in hollow fiber compression.

In the present paper, we describe the development of beam pointing and power stabilization systems for an intense femtosecond laser. The stabilization techniques eliminate the pointing and power fluctuations of a 1 kHz Ti:sapphire femtosecond laser. These techniques are then applied to hollow fiber pulse compression in order to stabilize the energy fluctuations and spectral variations for intense few-cycle pulse generation.

2. Experimental Setup

The beam stabilization system that we developed is a feedback control system composed of a PSD, an analog PID circuit, and a piezo-driven mirror. The PSD monitors the position of the incident beam on the sensor surface, and signals are then sent to the PID circuit for feedback control through the piezo-driven mirror, which actuates the beam direction control. The power stabilization system used in this study is composed of a power meter (PM), a digital PID controller and a Pockels cell driver. The output signals from the PM are sent to the digital PID controller, which controls the output voltage from the Pockels cell driver to change its transmittance for stabilization of the output power. In this work, we used a PM with an air-cooled thermopile sensor (Coherent PM-10) with a resolution of 1 mW and a response time of 2 sec.

The experimental setup is shown in Fig. 1. The power fluctuation was monitored using a zeroth-order diffraction beam from a grating compressor with PM #1 for feedback control. To stabilize the output power from a Ti:sapphire laser CPA (5 mJ, 25 fs, 1 kHz), the voltage applied to Pockels cell #1 was controlled. When the power stabilization system was evaluated outside the feedback loop, the output power was monitored with PM #2 after attenuation with neutral density filters (NDFs). The temporal variations of the output power were recorded on a personal computer (PC) at a sampling rate of 3.3 sample/s. Then, the output beam was loosely focused on to the hollow fiber input face using a lens. Before entering the hollow fiber, a small fraction, 3%, was split from the beam by a beam splitter (BS) and sent to the PSD for feedback control, where the distance between the BS and PSD was adjusted to be equal to that between the BS and the hollow fiber (~3 m). The beam was attenuated using NDFs before entering the PSD. The temporal variation in the beam position was recorded on a PC at a sampling rate of 4.4 ksample/s. The hollow fiber used in this study was a pressure-gradient hollow fiber with a length of 2.2 m and a core diameter of 500 µm, where Ne was supplied from the exit side of the fiber at a pressure of 1.4 atm. The spectrum broadened by self-phase modulation in the fiber was monitored with a spectrometer (Ocean Optics USB4000) with an integration time of 4 ms.

3. Results and Discussion

Figure 2 shows the temporal variations in the power (a) without and (b) with feedback control monitored inside and outside the loop.

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respectively, for inside and outside the feedback loop. Figure 3 shows the temporal variations in the beam position observed over 10 sec (a) horizontal and (b) vertical direction, where the red and blue curves signify without and with feedback control, respectively. Without feedback control, the beam fluctuations were ±87 µm (30 µm rms) in the horizontal direction and ±110 µm (42 µm rms) in the vertical direction. These fluctuations were stabilized by feedback control to within ±4.2 µm (1.0 µm rms) and ±4.7 µm (1.1 µm rms) in the horizontal and vertical directions, respectively. Frequency components up to 100 Hz were well stabilized by feedback control.

Next, we applied the beam pointing and power stabilization systems to hollow fiber compression. Figure 4 shows the temporal variations of the spectra broadened by self-phase modulation inside the hollow fiber (a) without and (b) with pointing and power stabilization. The spectra, broadened by self-phase modulation, were well stabilized by the feedback control. Here, we evaluate the spectral fluctuation from shot to shot. The deviation of an individual spectral profile $I_i(\lambda)$ from that averaged over a number of shots $\overline{I}(\lambda)$ is given by

$$\zeta_i = \frac{\int [I(\lambda) - I_i(\lambda)]d\lambda}{\int I(\lambda)d\lambda}$$

after integration over wavelength and normalized by the averaged value. The root-mean square values of the spectral fluctuation were calculated based on Eq. (1). Consequently, the stabilization system was shown to improve the spectral fluctuation from 16.2% rms to 3.5% rms. Figure 5 shows the temporal variation of the output power normalized by the average value. The power fluctuation was improved from 5.3% rms to 1.1% rms by pointing and power stabilization. Thus, the undesirable fluctuations due to input beam pointing and power fluctuations were significantly improved by the stabilization systems, resulting in a stabilized output power and a stable spectrum.

Fig. 3 Temporal variations in the beam position observed at PSD #1 (a) horizontal and (b) vertical direction with and without feedback control.

Fig. 4 Temporal variations of the spectra after passing through the hollow fiber (a) without and (b) with pointing and power stabilization in a false-color representation.
After the residual chirp in the output pulse was compensated with a set of chirped mirrors (Femtolasers BBCOMP), the compressed pulse duration was measured with spectral phase interferometry for direct electric field reconstruction (SPIDER). Consequently, pulse durations as short as 5.4 fs were obtained with an energy of 2.7 mJ.12)

4. Conclusion

In conclusion, we have developed a beam pointing and power stabilization system for high-power femtosecond lasers operating at a repetition rate of 1 kHz. Pointing fluctuations as large as 40 µm rms could be well stabilized to within 1 µm rms with the pointing stabilization system and the output power was improved from 0.32% rms to 0.15% rms by the power stabilization system. In consequence, the output spectrum after passing through a hollow fiber was significantly improved together with the output power. Based on these results, we were able to generate well-stabilized intense few-cycle pulses without any problems, such as damage to the fiber input face. These techniques will also be useful for stabilizing the CE phase after hollow fiber pulse compression.

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References


Fig. 5  Temporal variation of the output power passing through the hollow fiber with and without pointing and power stabilization.