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Output Energy Stabilization of Non-collinear Optical Parametric Amplifier

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Active stabilization loops were implimented in a non-collinear optical parametric amplifier (NOPA) to reduce output pulse energy fluctuation. Proportional-integral-derivative feedback stabilizations of pump and seed energy reduced fluctuation of each controlled parameters more than 80% and resulted in more than 60% reduction of the final NOPA output energy fluctuation. This simple stabilization scheme is expected not to affect the capability of NOPA to generate ultrashort pulses, and hence this scheme can be applied to improve signal-to-noise ratio of the data obtained in experiments using NOPA.

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A non-collinear optical parametric amplifier (NOPA)[1–5] is a valuable tool in spectroscopy, because it enables the generation of tunable transform-limited light pulses with the pulse energy of 50 nJ which are suitable for ultrafast pump–probe in visible region. Because the output spectrum of a NOPA is smooth and relatively stable in shape, without sharp peaks nor valleys, performing spectrally resolved real-time spectroscopy experiment using NOPA provides invaluable information such as molecular motion or chemical reaction processes.[6–9] Its shorter than 5 fs pulse duration of makes it possible to observe high ($>3000\,\mathrm{cm}^{-1}$) frequency molecular vibration directly.[4]

However, for performing such spectroscopic experiment, NOPA output energy fluctuation is sometimes problematic. Because NOPA amplifies its seed pulse by several orders of magnitudes (×3000), slight variation in pump power is also amplified resulting in a large variation of the output power. Furthermore, seed pulse energy is also susceptible to the change in input pulse energy and duration, because self-phase modulation process used in the seed generation is highly nonlinear. In the present case, stability of the output energy from the NOPA system which was originally developed in our group has been changing in unpredictable way,[4] affected by temperature variation, humidity, and air turbulances. It changed day-to-day from a few percent (peak-to-peak with the integration time of 500 ms) to as much as 50% (the same, Fig. 1). Under bad condition, fluctuation of NOPA output energy surpasses 20% and large noise appears in delta-T signal, rendering the reproducible results of pump–probe spectroscopy impossible to be obtained.

In order to solve this problem, we stabilized the pulse energy at a few points in the NOPA system by feedback control systems, resulting in a significant improvement in the stability of NOPA output energy. Note that the feedback function of the control in this study is for the stabilization of the NOPA pulse energy, not is not for the pulse carrier-envelope phase whose stabilization methods are studied by many groups.[10–12] For spectroscopy the pulse energy stabilization is crucial to obtain weak signals with high signal-to-noise ratio.

Figure 2 is the optical block diagram of the NOPA system in the present study.

The NOPA was pumped by the second hamonic (wavelength: 400 nm) generated in a β-barium borate (BBO) crystal from the output of Ti:sapphire regenererative amplifier with peak wavelength of 800 nm and repetition rate of 5 kHz. The seed of the NOPA with the wavelength extending from 530 to 750 nm was generated by the self-phase modulation of the fundamental 800 nm light in a sapphire plate. After the seed is transmitted through an interference filter for the removal of the 800-nm fundamental, these two beams of the pump and seed were focused in another BBO crystal with the internal non-collinear angle of 3.7° to realize the amplification with maximum gain bandwidth. The seed light was amplified as the signal beam. The amplified signal beam was then compressed with a chirped mirror pair and a prism pair, and the compressed pulse was guided to pump–probe spectroscopy setup.

The NOPA stabilization was achieved in two steps: the investigation of NOPA instability and the implimentation of feedback control systems based on the result of first step.

In the first step, we tried to identify the causes of the NOPA output energy instability. For this purpose, we constructed a system which continuously monitors and records the pulse energy at several points in the system. The points of observation were, (1) output of regenerative amplifier (from here on we call it “Amp.”), (2) NOPA pump pulse (“SH”), (3) NOPA seed pulse after 800-nm-rejecting filter (“Cont.”), (4) Ti:sapphire oscillator output seeding the regenerative amplifier (“Osc.”). We detected the average power of each beam at first picking out a part of the beam using a partial reflector, detecting stray reflection light from an optical component, or detecting leakage transmission light of a mirror. The devices used for conversion to electric signal were silicon PIN photodiodes. The electric signals were converted to digital data by analog–digital converters (ADC) with sampling interval of 50 ms and recorded by a personal computer (PC). Because all signals other than that from oscillator were pulse trains with a 5 kHz repetition rate and the fluctuations under investigation had the frequency of about several Hz, we eliminated the 5 kHz component using 6-order RC filters in front of ADC. The time constant of the RC filter was about 30 ms ($1/e$ time). We made sure that 800-nm component of “Cont.” was smaller than 5% of a measured value.

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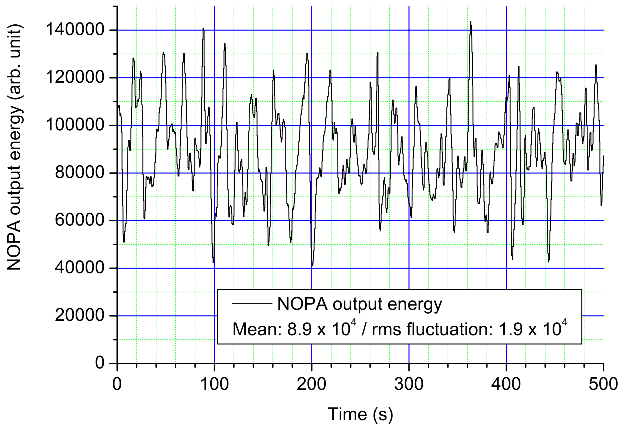

Fig. 1. (Color online) Output energy fluctuation of non-collinear optical parametric amplifier without stabilization.

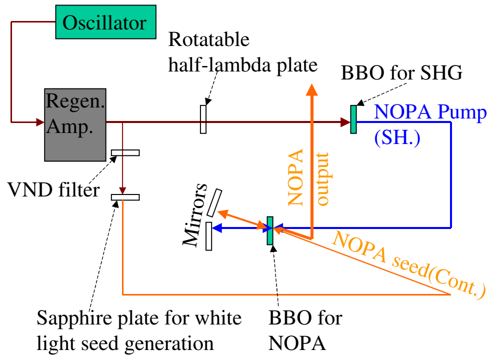

Fig. 2. (Color online) Optical block diagram of non-collinear optical parametric amplifier.

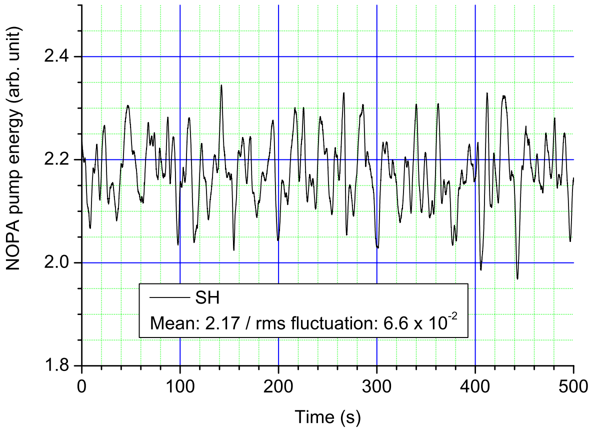

Fig. 3. (Color online) Pump energy fluctuation of non-collinear optical parametric amplifier without stabilization.

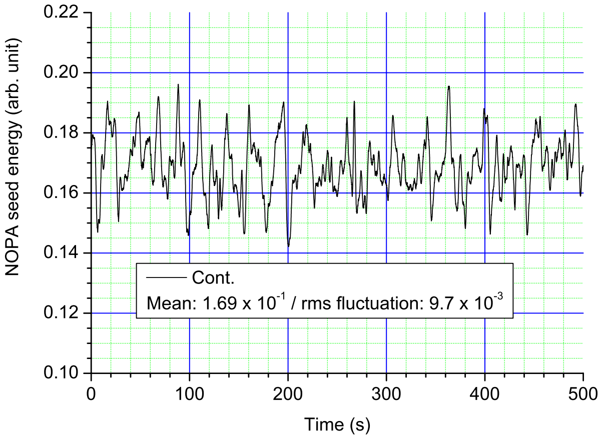

Fig. 4. (Color online) Seed energy fluctuation of non-collinear optical parametric amplifier without stabilization.

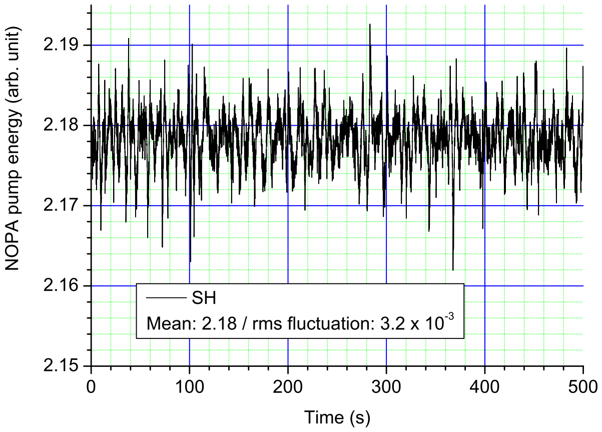

Fig. 5. (Color online) Pump energy fluctuation of non-collinear optical parametric amplifier with feedback control.

By analyzing the monitored signals, it was found that fluctuations of "Amp." and "Osc." were less than 1% (peak-to-peak) satisfying the specification of each laser. When NOPA output energy was stable (peak-to-peak fluctuation of under 10%), "SH" and "Cont." fluctuated about 3–5% (peak-to-peak). However, when NOPA output energy was unstable (peak-to-peak fluctuation of over 40%), they showed fluctuations of 15 and 30% each (Figs. 3 and 4).

We found that the fluctuation of NOPA output energy was strongly correlated with that of "SH". After the stabilization of "SH", with its peak-to-peak fluctuation of below 1%, NOPA output energy fluctuation was strongly correlated with the fluctuation of "Cont." It was found that there were no significant correlations with the fluctuation of "Amp." or "Osc."

In the second step, we implimented two feedback control systems into the NOPA setup. The first feedback control system was for the stabilization of NOPA pump energy ("SH"). In order to stabilize the NOPA pump energy, the second harmonic generation efficiency was changed by rotating the polarization of fundamental laser field at 800 nm. To rotate the polarization of the fundamental continuously, the beam was transmitted through a half-lambda plate which is rotatable around its optical axis by a motorized rotation stage controlled by PC. The feedback actuator was selected because of the observed fluctuation period of a few seconds. The algorithm used was a proportional-integral-derivative (PID) controller. The time interval of feedback was chosen to be 50 ms, in accordance with the response time of rotation stage.

The first feedback control resulted in the reduction of fluctuation of "SH" by as much as 80%, down to the peak-to-peak value of 3% (Fig. 5). The fluctuation of NOPA output energy was also reduced by about 30%.

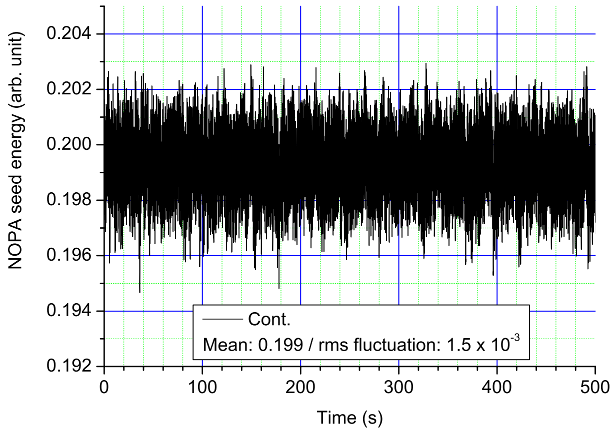

Fig. 6. (Color online) Seed energy fluctuation of non-collinear optical parametric amplifier with feedback control.

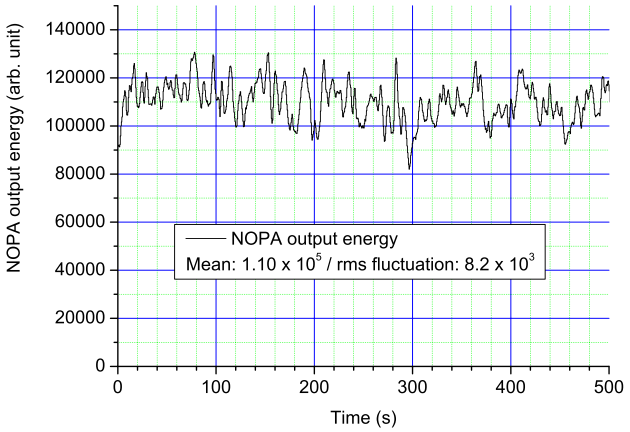

Fig. 7. (Color online) Output energy fluctuation of non-collinear optical parametric amplifier with two feedback loops on.

The second feedback control system was implimented because the improvement of NOPA output energy stability with the first feedback control system was unsatisfactory. The second feedback control system was for the stabilization of NOPA seed energy ("Cont.").

To operate upon NOPA seed energy, the energy of 800-nm pulse used for NOPA seed generation by self-phase modulation was changed. The energy of 800-nm pulse was originally manually adjusted by transmitting a variable neutral density filter (VND) placed before the sapphire plate inside which self-phase modulation takes place. We mounted the VND onto a PC-controlled motorized rotation stage to make the pulse energy controllable. The feedback control algorithm used and the time interval were the same as that of the first feedback control system.

The second feedback control resulted in 80% reduction of seed energy fluctuation (Fig. 6). With both feedback loop on, NOPA output energy fluctuation was reduced by 60% (Fig. 7). The quantitative result of stabilization is summerized in Table I.

Table I. Effect of stabilization on the rms fluctuation of NOPA (unit: %).

	Freerun	Stabilized	Reduction
Pump	3.0	0.15	95
Seed	5.7	0.73	87
NOPA	21	7.4	65

Further improvement of the present study may considered to be possible as follows. The NOPA output energy can be directly stabilized by taking NOPA output energy as the input of feedback and to operate upon NOPA pump and/or seed energy. However, such approach were not taken because of the following reason.

The NOPA requires daily adjustment in order to achieve short pulse width. In the adjustment process we depend heavily upon the second harmonic intensity of NOPA output for the rough estimation of pulse width. The fluctuation of NOPA output is the most problematic and the stabilization is most important in such a situation. However, because the adjustment requires the tuning of many parameters and any parameter change leads to the change of NOPA output energy, direct stabilization of NOPA output energy during the adjustment process is considered to produce completely uncontrollable result.

In summary, stabilization of NOPA was implemented by the two PID feedback loops stabilizing pump and seed pulse energy to reduce final output energy fluctuation. Each stabilization loop reduced fluctuation of each controlled values by more than 80%. In combination, final NOPA output energy fluctuation was reduced by more than 60%. In principle, this scheme will not affect capability of NOPA to generate ultrashort pulses. This simple yet effective stabilization scheme will make it possible to improve the signal-to-noise ratio of the data to be obtained in pump–probe spectroscopy experiment using NOPA.

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