Development of an ultrabroad-band regenerative amplifier with a mirrorless cavity and generation of sub-20 fs pulses in terawatt regime with an adaptive phase controller

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We have developed an ultrabroad-band regenerative amplifier with a mirrorless cavity to eliminate the limitation of bandwidth of dielectric coats on cavity mirrors. A large amount of material dispersion in Pellin-Broca prisms which are used instead of the cavity mirrors is compensated using a hybrid technique of Brewster prism pairs in the regenerative amplifier and an adaptive phase controller of a liquid-crystal spatial light modulator. We obtained a 16 fs pulse width with an energy of 13 mJ, which was the highest energy in the sub-20 fs regime using the adaptive phase controller.

Introduction

High-energy ultrashort pulse sources have been playing important roles in many fields of physics and chemistry. The shortest pulse of high-order harmonics was obtained using a sub-20 fs, mJ-class Ti:sapphire laser [1] and control of the chemical reactions is a novel field in the application of the ultrashort pulse sources with phase control.[2] The energy of sub-20 fs laser sources, however, has been limited to the 1–2 millijoule level [3–6] except in one system developed at the Japan Atomic Energy Research Institute (JAERI).[7] The most important issue for the amplification of sub-20-fs pulses is gain narrowing of the spectrum, so that the entire mJ-class system adopts multipass configurations of the amplifiers which suppress the gain narrowing of the spectrum owing to high gain in the amplifiers and seed spectrum shaping.

The situation changes if we require energies higher than 10 mJ. The gain narrowing of the spectrum can no longer maintain the sub-20-fs range because of a large amplification of the seed pulse ratio. We need active control of the spectrum during the amplification; this was realized by Barty *et al.* using a regenerative amplifier, named "regenerative pulse shaping".[8] High-damage-threshold dielectric coats at 0° incidence on mirrors in the regenerative amplifier, on the other hand, limit the bandwidth of gain in the cavity of the amplifier.[9]

Another important issue for sub-20-fs amplification is phase control over a broad range of the spectrum. Because the optical path length of dispersive materials in a mJ-class multipass amplifier system is much shorter than that in a regenerative amplifier, amplified pulses experience a relatively small amount of dispersion in the former system and a standard stretch-compression scheme can generate 20 fs pulses.[10]

The issue of phase control in the sub-20 fs regime cannot be solved with the aforementioned scheme even for the shorter optical path length. Thus, most of the sub-20-fs systems developed so far introduce novel instruments such as a special stretcher,[7] chirped mirrors,[3] an acousto-optic programmable dispersive filter (AOPDF),[4] a liquid-crystal (LC) spatial light modulator (SLM),[11–13] and a deformable mirror [5] for compensation of high-order dispersions and unexpected complex phase errors.

In this paper, we report on a novel configuration of the regenerative amplifier, which consists of Pellin-Broca prisms instead of dielectric coated mirrors for the amplification of the sub-20-fs pulses. Total reflections in the prisms do not limit the bandwidth in the spectral range of the Ti:sapphire laser, thus there is no need to spend time strictly tuning the spectral range of reflection on cavity mirrors to the gain bandwidth of Ti:sapphire. Most of the material dispersion in the prisms is compensated using a combination of Brewster prism pairs in the cavity of the regenerative amplifier. An LC-SLM on a Fourier plane in an extra zero-dispersion stretcher is used to achieve the adaptive compensation of residual phase errors. A spectral width exceeding 100 nm for 30 mJ pulses amplified by a system consisting of a four-pass amplifier following the regenerative amplifier was obtained and the pulses are compressed to the 16-fs pulse width with an energy of 13 mJ.

Experiment

The experimental setup of the laser is a typical chirped pulse amplification (CPA) system consisting of a mode-locked oscillator, an Offner stretcher,[14] a regenerative amplifier, a four-pass amplifier, and a compressor. An adaptive phase controller is placed between the stretcher and the regenerative amplifier as shown in Fig. 1.

A mode-locked oscillator with chirped mirrors (FEMTO LASERS Produktions, Femtosource Scientific PRO) pumped by the second harmonic of a laser-diode-pumped Nd:YVO_4 laser (Spectra Physics, Millennia V) generates an ~10 fs pulse train, to which a positive chirp is given by the Offner stretcher to obtain a sufficiently long pulsewidth of about 400 ps dur-

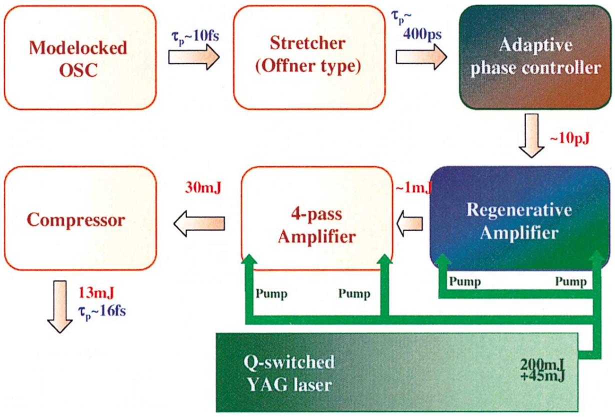

Fig. 1. Outline of the laser system.

ing the amplification. The stretcher consists of a grating with a groove density of 1200 lines/mm (Richardson Grating Laboratory, 5315BK-360) and of a 40-cm-wide concave mirror and a 15-cm-wide convex mirror with curvatures of 1 m and -0.5 m, respectively. Although surface figure on these concave and convex mirrors is within $\lambda/8$ (IK Technology Co., Ltd.), which does not guarantee an ideal phase within a range of the spectrum for sub-20-fs pulses,[15] an adaptive phase controller followed by the stretcher can compensate for an unexpected residual phase error if it exists.

The configuration of the adaptive phase controller [11,12] is that of a typical 4-f telescope consisting of two concave mirrors with two gratings and an LC-SLM (Cambridge Research & Instrumentation, SLM-128) which is placed on the Fourier plane of the concave mirrors. The period of pixels in the LC-SLM is 100 μm (97 μm width and 3 μm gap), which correspond to the 0.79 THz optical bandwidth of a spatially dispersed beam with a grating (Richardson Grating Lab., 53-04-BK-790) at the incidence of the controller.

The regenerative amplifier using a ring cavity is the key component of this laser system, as shown in Fig. 2 (a). The original concept of this type of ring cavity for a regenerative amplifier was proposed by Yang and Walker.[16] In the regenerative amplifier demonstrated by Yang *et al.*, high reflection of an s-polarized beam at an incidence angle of 45° to a high-damage threshold dielectric coat can cover a spectral range of 100 nm [17] which may be sufficient for a temporal resolution of sub-20 fs, however, the cavity must be vertically configured

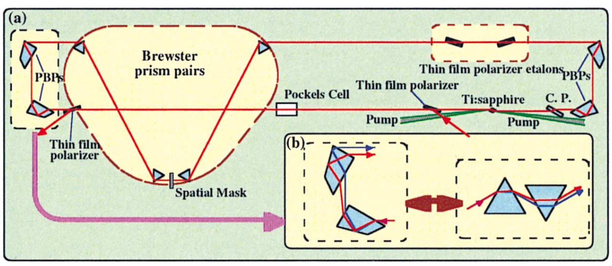

Fig. 2. (a) Schematic of the mirrorless regenerative amplifier. PBP, Pellin-Broca prism; C. P., compensating plate for spectral component spatially decomposed by the Ti:sapphire rod. (b) The equivalence of a Bellin-Broca prism pair to a Brewster prism pair.

to a optical table to keep s-polarized reflection on the cavity mirrors.

The total reflection on the surface of a glass material, on the other hand, has a wide range of reflectivity to p-polarized light, thus the ring cavity can be placed on the optical table horizontally without limiting the spectral width. The first choice of this type of total reflector is a right-angle prism with normal incidence to an input and an output surface which must be anti-reflection coated to ensure the minimum loss in the cavity. We adopt, however, a Brewster-incidence prism with the total reflection, called a Pellin-Broca prism (PBP); this is used instead of cavity mirrors. The Brewster-incidence of the PBP eliminates the risk of optical damage to the anti-reflection coating of normal incidence on a right-angle prism.

As is the nature of the Brewster-incidence prism, a laser beam is diverged in each spectral component by the PBP; thus, another PBP is needed for collimation, as shown in Fig. 2 (b). Although the dispersion of the PBP pair is equivalent to that of a Brewster prism pair as also shown in Fig. 2 (b), the optical path length is too long to induce a negative group delay dispersion (GDD).

Reflectors of the cavity in the regenerative amplifier consist of two pairs of PBPs made of silica as a low-dispersion material and we added two pairs of Brewster prisms of LAH64 glass (OHARA) to reduce the positive GDD and to induce a negative third-order dispersion (TOD) for a hybrid compensation with a mismatch of incidence angles to the gratings of the stretcher and the compressor.[18–20]

This compensation technique utilizing Brewster prisms in the regenerative amplifier makes it possible to flatten the phase in the spectral range in order to generating a 30–20-fs pulse as described in reference 15, whereas it is not sufficient for application to the sub-20-fs regime because (1) it cannot correct phase errors at both edges of the spectrum and (2) modulation of the phase induced by etalons, which are inserted into the cavity for spectral control, significantly affects the characteristics of the sub-20-fs pulses.

We show the phases in the laser system calculated with a ray tracing method in Fig. 3. A dashed curve represents the result of the compensation method for the Brewster prism pair in the regenerative amplifier used so far.[18] Modulation with a period of about 27 THz at the center is responsible for the etalons. The inverse Fourier transform of a model spectrum for a 14-fs pulse as a transform limit resulted in a modulated pulse shape with this phase, shown as a dashed curve in the inset of Fig. 3. Adaptive phase compensation (APC) with the LC-SLM dramatically improved the situation as shown in a solid curve in Fig. 3 which was a calculated result based on the analysis of Wefers and Nelson.[11] Although a small amount of phase modulation still remains for the discretized nature of pixels in the LC-SLM and for a mismatch of sizes of the pixels and the beam diameter, the compensated phase generates an almost transform-limited pulse of 14 fs as a solid curve in the inset.

A Brewster-cut Ti:sapphire rod in the regenerative amplifier is pumped from both ends by the second harmonic of a Q-switched Nd:YAG laser (HOYA Continuum, Surelite I-10) at a repetition rate of 10 Hz. The spectral components spatially

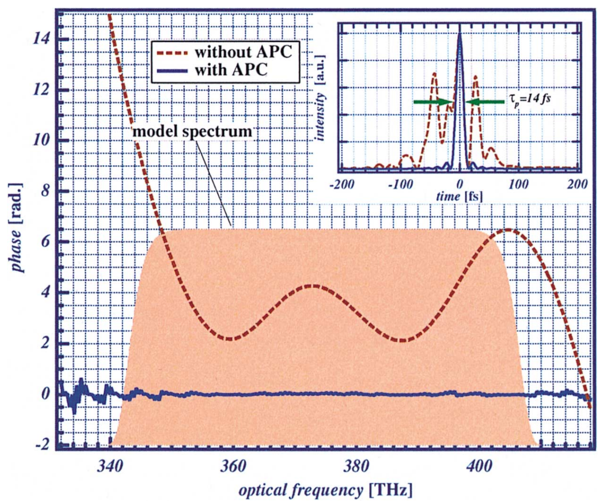

Fig. 3. Calculated phases based on a ray trace. A dashed curve; without adaptive phase compensation (APC), a solid curve; with APC. Temporal profiles calculated from a model spectrum shown as a hatched area are also shown in an inset.

decomposed by the Ti:sapphire rod are composed using a plate of BK7 glass. The Pockels cell (Cleveland Crystal, Impact 8) placed between two thin film polarizers injects a seed pulse with an applied $\lambda/2$ voltage window of 6 ns and rejects the amplified pulse with the second $\lambda/2$ voltage after saturation of the amplification is achieved. Two thin film polarizer etalons and a spatial mask at the spatially dispersed end of the Brewster prism pairs give spectral-dependent losses to the cavity such that we can obtain a broad spectrum. The tuning range of this cavity was measured with a knife edge that is replaced by the spatial mask. Spectra of the self-oscillation at the edge of the tuning range are shown in Fig. 4 by a dashed curve and a dotted curve, which verify the ability of the amplifer to achieve the spectral width of ~130 nm.

We were able to adjust the output spectrum from the regenerative amplifier with the spatial mask and the etalons to obtain a spectral width greater than 100 nm at the edge, although we made the central dip of the spectrum deep and

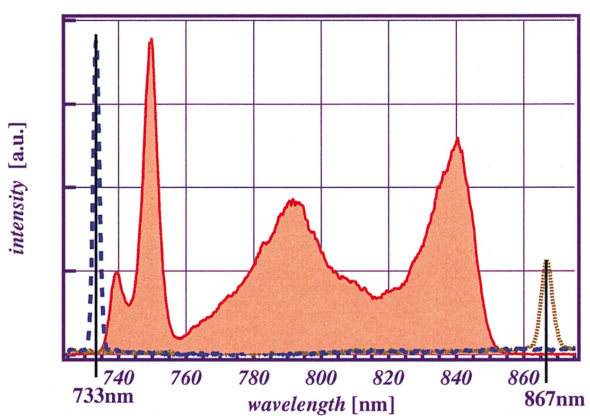

Fig. 4. A dashed curve and a dotted curve show the shortest and longest spectral limits, respectively, of self oscillations in the regenerative amplifier. The solid curve shows the spectrum of an amplified pulse.

wide so that it was filled after four-pass amplification.

The energy of the output pulse was ~1 mJ, which was less than 1% of the pumping energy of 135 mJ. This low efficiency may be due to the loss at the anti-reflection coatings on the outside surfaces of the etalons because the incidence angles of the etalons were set to be slightly different from the expected ones for the adjustment of the spectrum.

The pulse from the regenerative amplifier goes through a Faraday isolator and is sent to the four-pass amplifier consisting of a Brewster-cut Ti:sapphire rod and folding mirrors. Reflections of the s-polarized beam on six surfaces of the folding mirrors give almost no limit to the amplified spectral width. Two pumping beams are relay imaged on both surfaces of the rod at the center of the four-pass configuration. One of the beams with an energy of 65 mJ is the residual second harmonic of the Q-switched Nd:YAG laser used for the pumping of the regenerative amplifier, and the other beam with an energy of 45 mJ is generated by a residual fundamental beam in an extra type II KDP crystal placed behind a high reflector for the primary second harmonic. With the help of this extra 45 mJ pumping source, we obtained an energy of 30 mJ for the output, although we observed a ~20-% drift of the output energy caused by the poor stability of hand-made thermo controller of the extra KDP crystal.

The telescope with a concave mirror and a convex mirror magnifies the beam diameter of the output pulse to approximately 2 cm and sends the pulse to the compressor. We note that the convex mirror of the telescope is the only mirror with a high-damage-threshold coat of 0° incidence in the entire laser system.

The measured spectrum of the compressor is shown in Fig. 4. Although modulations in the spectrum cause ripples at the feet of a temporal profile calculated from the inverse Fourier transform with the constant phase, this spectrum has a sufficient spectral range for generating a 16 fs pulse. The energy of the compressed pulse was 13 mJ, which was about 43% of the input pulse.

The compressor, consisting of two gratings with groove densities of 1200 lines/mm (Richardson Grating Lab., 5315BK-360) and a gold-coated roof reflector, was first arranged to obtain the shortest pulse without APC. The phase measured by spectral phase interferometry for direct electric-field reconstruction (SPIDER)[21] is shown as a dashed curve in Fig. 5.

The observed phase modulation with a period of ~30 THz is due to the etalons in the regenerative amplifier. The solid curve in Fig. 5, on the other hand, represents a phase controlled by the adaptive phase controller of the LC-SLM. Each pixel in the LC-SLM producing an inverse phase in the dashed curve compensates the phase modulation.

Although measured autocorrelation traces change in accordance with the change of the spectrum, differences in phase between the cases with and without APC are reflected in the autocorrelation traces shown by circles in Fig. 6 (a) and 6 (b). Compared to the trace in Fig. 6 (a) with large side-shoulders, which stand for modulations in a temporal profile, the trace in Fig. 6 (b) shows a reduction of the height of the side-shoulders. The autocorrelation trace calculated from the measured spectrum in Fig. 4 and the phase in Fig. 5 is

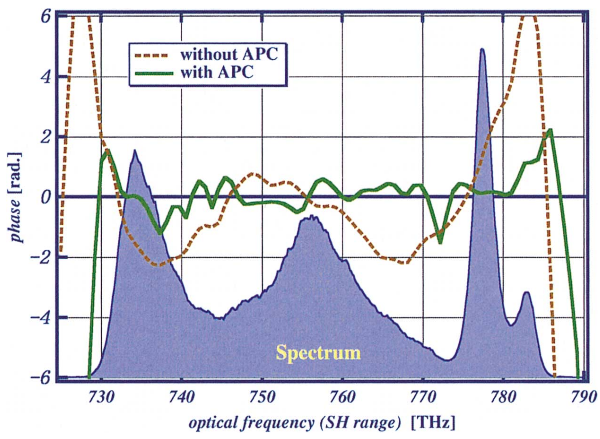

Fig. 5. Measured phases of amplified pulses by SPIDER. Horizontal axis is shifted to the second harmonic (SH) range of the measured pulses for sum frequency generations of SPIDER measurement.

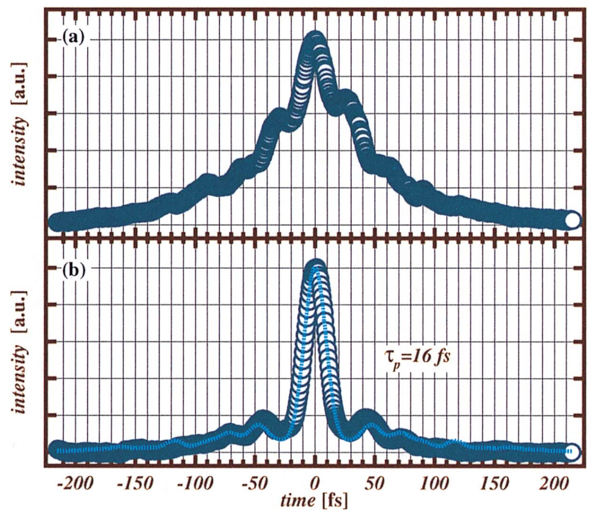

Fig. 6. Autocorrelation traces (a) without APC, and (b) with APC.

consistent with the measured trace shown in Fig. 6 (b). We determined the pulse width to be 16 fs at full-width at half maximum, although there are some ripples at the feet of the pulse.

Summary

In summary, we have developed a TW-class laser system in the sub-20-fs regime. The unique features of a mirrorless cavity and APC enabled ultrabroad-band amplification in a regenerative amplifier and 16 fs pulses with an energy of 13 mJ, which is the highest energy achieved to the best of our knowledge for adaptively phase-compensated sub-20-fs pulses.

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