Nd:glass diode-pumped regenerative amplifier, multimillijoule short-pulse chirped-pulse-amplifier laser

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We have built a diode-pumped Nd:glass regenerative amplifier that is able to produce energies up to 20 mJ within a 470-fs pulse duration at a 1-Hz repetition rate. We obtained this amplifier by using specific intracavity components such as a phase mirror and a birefringent filter to generate a large spatial mode and a large spectral width.

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A regenerative amplifier is a good candidate to serve as a high-energy compact laser source of short pulses. A new intracavity reflective mode shaping component maximizes the extraction energy of a side diode-pumped medium.[1] At the same time we use an intracavity spectral filter to overcome spectral gain narrowing. With this scheme we can amplify a chirped pulse by using a chirped-pulse-amplifier (CPA) technique.[2] The diode-pumped amplifier needs to operate at a wavelength of 1053 nm, based on the use of a Nd:glass amplifier. This medium has an amplifying spectrum that is broad enough to deal with subpicosecond pulses. To enlarge the spectrum of this laser, one could choose to use another medium such as Yb:YAG, but the saturation fluence would be low and the emission peak of ~1030 nm could not be adapted for a power chain front end. Another solution would be to use an intracavity spectral filter to overcome spectral gain narrowing. Energy would be lost, but a large mode cavity could increase the overlap between the laser beam and the gain area. To obtain a uniformly flat profile it is possible to use a far-field amplitude mask[3] or an intermediate-field phase mask.[4–6] The advantage of using a phase mask is its superior ability to extract energy compared with an amplitude mask, which would induce energy losses. The generation of flat-topped mode shaping is also important for increasing the extraction energy in a regenerative diode-pumped cavity.[1] In a regenerative amplifier it is possible to use a spectral filter such as an intracavity Fabry–Perot etalon or a birefringent filter.[7–9] With this optical component it is possible to overcome gain narrowing and amplify a chirped pulse. We describe below the use of a phase mirror in a regenerative amplifier to enlarge mode size and to increase extracted energy. The intracavity spectrum is shaped by a birefringent filter to enlarge the spectrum. The output chirped pulse is compressed by a grating pair to produce a short pulse. The short pulse is then analyzed by an autocorrelator device to aid in estimating the pulse duration. In the first part of this Letter we describe the modal and energetic characteristics of this cavity; in the second, the CPA performance.

A schematic view of the experiment is shown in Fig. 1. The initial short pulse is generated by a diode-pumped laser [TB product (TBP)] that is mode-locked by a semiconductor saturable-absorber mirror. It generates 100-MHz short pulses with an 8-nm spectrum, 200-fs pulse duration, and an energy of 1 nJ. This pulse is stretched by a system of two gratings coupled to an afocal system to achieve 800-ps operation. The energy is amplified in a regenerative

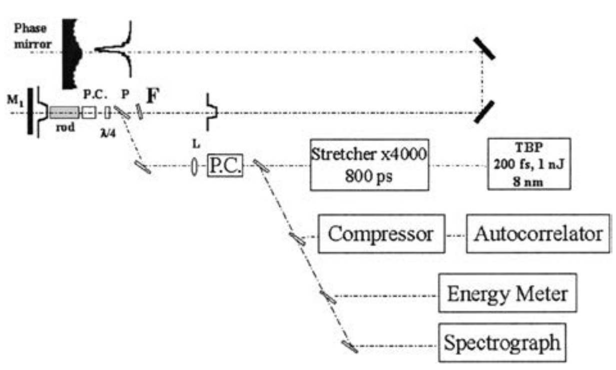

Fig. 1. Schematic diagram of the CPA experiment: F, birefringent filter; P, polarizer; P.C., Pockels cell; L, lens. We show the chirped-pulse injection scheme and all the diagnostics. The super-Gaussian circular mode is imaging just behind plane mirror M_1. We measured the output energy, the cavity spectrum, and the pulse duration with the autocorrelator device.

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amplifier. The amplifying medium is neodymium-doped phosphate glass (Hoya LHG8; 4 mm × 4 mm × 80 mm) side pumped with eight stacks of six diode bars (Thomson-CSF) that can deliver 2.9 kW of power for 400 μs. Because there is no cooling system, to limit the phase distortion that is due to main thermal loading we fixed the repetition rate at 1 Hz. The phase mirror is the main component of the cavity and permits the shaping of a circular super-Gaussian mode. The method of intracavity mode shaping consists of conjugating the diffracted field after propagation of a super-Gaussian circular mode on the phase mirror, which defines the fundamental mode of the cavity.[5] A phase mirror was selected instead of a phase plate to minimize intracavity loss. The initial mirror is concave, with a radius of 6 m. The phase mask is achieved by ion-beam etching.[10]

Figure 2 shows a profile of the dephasing of the mirror with the initial 6-m curvature of the mirror removed and a theoretical profile compared with the interferometrically measured actual mirror. The total measured phase is the sum of two measurements: a profilometer measurement for the center area and an interferometric measurement for global figuring. The peak-to-valley distance of the profile is ~1 μm for a 30-mm diameter. We observed a good agreement between specifications and measurement, within 5% rms accuracy.

When this phase mirror is used, the fundamental mode of the regenerative cavity becomes super-Gaussian. The length of the cavity is optimized to maximize the diffraction losses of the next-higher mode of the cavity.[1] The optimal length of the cavity, which is approximately 4.9 m, depends essentially on the mode size and is close to the Rayleigh length of the beam. Figure 3(a) shows the intracavity fundamental mode. Its shape is circular and super-Gaussian. This mode profile was measured with an 8-bit CCD camera immediately after the plane mirror cavity. A comparison of the expected shape and the experimental measurement is made in Fig. 3(b). We have also plotted simulations of the mode shape produced by the cavity, including the measured phase of the mirror (Fig. 2). Both results are in good agreement with specifications. A simulation of the phase mirror's interferometric measurement yielded a 2.6-mm mode diameter with the 15th-order super-Gaussian, whereas the specification mode is 2.7-mm diameter with a 20th-order super-Gaussian. The direct measurement gave a 15th-order super-Gaussian mode with a diameter of 3.0 ± 0.2 mm (FWHM), with 10% rms of modulation at the top of the beam.

The Findlay–Clay method was implemented to characterize losses and gain in the cavity.[11] We measured the threshold current diode versus cavity losses induced by rotation of the intracavity quarter-wave plate. A plot of threshold current versus losses showed the losses and the amplification coefficient during one trip in the cavity. The experimental results yielded the value $L = 12\%$ for the single-pass losses. The expected linear relation between pump energy E_p and amplification coefficient $g_0 l$ is $g_0 l = K E_p$, where $K = 0.5235\ \mathrm{J}^{-1}$. The pump energy was 0.6–1.3 J, and the energy extracted without the spectral filter was 8–80 mJ at 1 Hz. Figure 4 compares the experimental results with theory. The experimental results, which are in good agreement with regenerative cavity modeling,[12] allow us to express the extracted energy (E_{out}) versus amplification coefficient ($g_0 l$) as follows: $E_{\mathrm{out}} = F_{\mathrm{sat}} S[g_0 l - L - L \ln(g_0 l/L)]$, where F_{sat} is the saturation fluence, S is the beam mode area, and L is the loss per round trip of the cavity.

However, it is well known that a high regenerative cavity gain implies strong spectral gain narrowing. With an injected Lorentzian spectral bandwidth of 8 nm FWHM, the output spectrum is 1.2 nm (FWHM). To overcome spectral gain narrowing and to amplify a

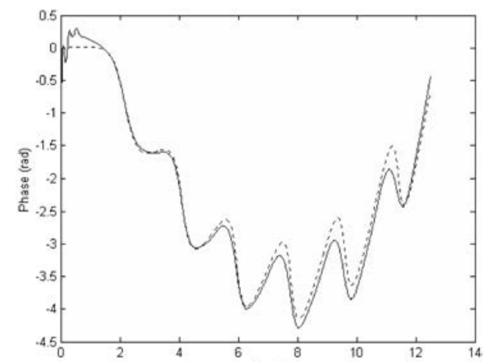

Fig. 2. Phase profiles of the phase mirror: specification (solid curve), interferometric measurement (dashed curve). The phase versus radius r is given without curvature ($R = 6$ m), and $r = 0$ is the mode center.

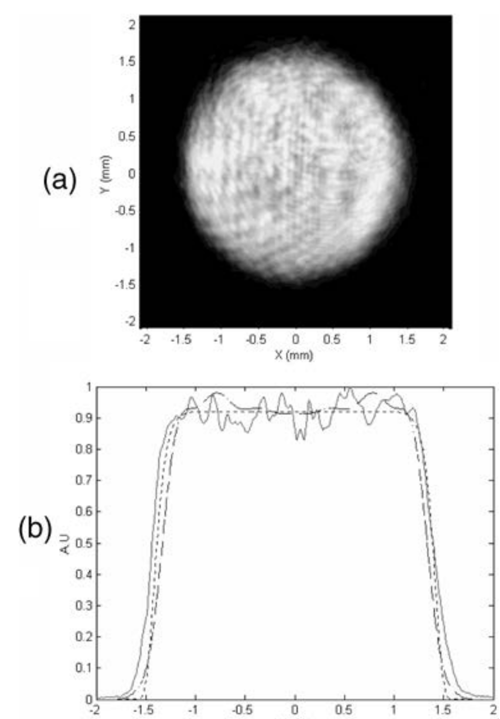

Fig. 3. Experimental results: (a) circular mode measurement with the intracavity phase mirror, (b) experimental result (solid curve), simulations with the phase mirror measurement (dashed curve), and specification (dotted curve).

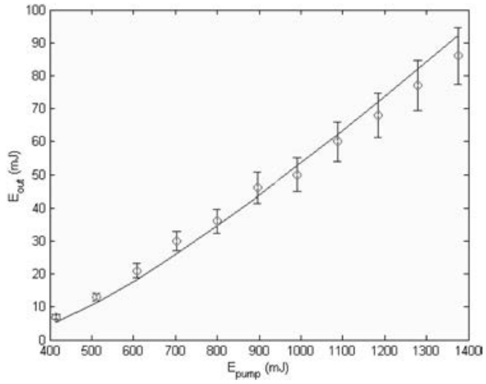

Fig. 4. Output cavity energy versus diode-pumped energy for a Q-switch cavity without a birefringent filter. The measurement points and the model curve given in Ref. 12 are shown.

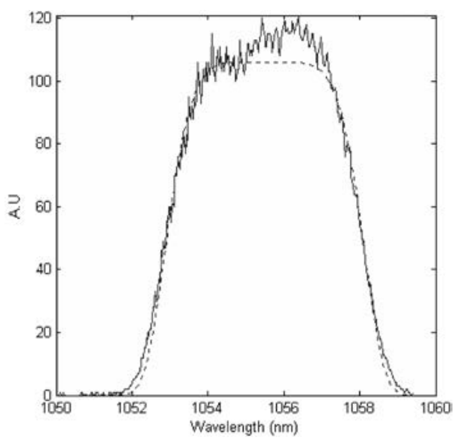

Fig. 5. Experimental spectrum: measurement (solid curve) and 6th-order super-Gaussian fitted curve (5.1 nm FWHM). This broadband spectrum was obtained with the intracavity birefringent plate.

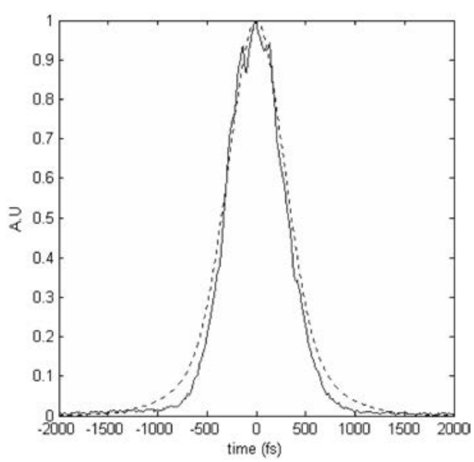

Fig. 6. Autocorrelation signal measurement: experimental results (solid curve) and simulation obtained with the experimental spectrum (dashed curve).

broadband spectrum we inserted an intracavity birefringent filter. This filter permits a sinusoidal spectral amplitude shape to be generated.[8] A 5-mm-thick quartz plate near the Brewster angle was selected. Axial rotation allows us to control and to enlarge the pulse spectrum's shape. Figure 5 shows the spectral profile after amplification, which has been fitted to a 6th-order super-Gaussian shape to yield 5.1 nm FWHM. An autocorrelation trace, $\tau_{\mathrm{autoco}} = 700$ fs, was measured. From the spectral measurement it is possible to simulate the autocorrelator signal immediately after the grating compressor device. With the assumption of a Fourier-transform-limited pulse, a simple relation between the FWHM autocorrelation duration (τ_{autoco}) and the FWHM pulse duration (τ_{pulse}) can be found. Our simulations gave $\tau_{\mathrm{pulse}} = \tau_{\mathrm{autoco}}/1.5$. In Fig. 6 the autocorrelation profile and the simulation profile are plotted. The good agreement between the simulations and the measurements shows that the spectral phase distortion is weak but that the high-order super-Gaussian spectral shape generates postpulses and prepulses. We found a pulse duration of $\tau_{\mathrm{pulse}} = 470$ fs with an output energy greater than 20 mJ.

In conclusion, we have described extracted energy enhanced by a phase mirror, which yields a 15th-order circular super-Gaussian fundamental mode shape. We have shown that an intracavity spectral filter can overcome spectral gain narrowing. This scheme allows a chirped pulse to be amplified with a 5-nm output spectrum. Using a compressor device, we obtained a pulse duration of 470 fs with an energy of 20 mJ, leading to an output of 0.04 TW of power. For further advancement, this scheme could be enhanced to the 100-mJ level by use of a cavity with only reflective components to minimize intracavity losses.

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