Generation of 14.8-fs pulses in a spatially dispersed amplifier

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We demonstrate amplification and compression of 110-nm broad spectra in a spatially dispersed amplifier for what is believed to be the first time and generate 14.8-fs pulses with 450 μJ of energy at a repetition rate of 1 kHz. The amplifier concept is scalable in energy and allows for spectral shaping, which was demonstrated and compared with numerical simulations and showed excellent agreement. © 2004 Optical Society of America

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The rapid advance of ultrashort amplified laser technology into a mature research tool has inspired its widespread use. Ultrashort laser pulses, with durations of less than 10 fs, are generated exclusively by use of gas-filled capillaries with subsequent compression.[1] The inherent limitations of this technique—in terms of energy scalability—demand further investigations into direct ultrabroadband chirped-pulse amplification. However, three main problems are associated with this procedure: The first is thermally induced lensing and aberrations, which can be overcome by cryogenic cooling[2] or by careful design. The second problem is nonlinear effects, which one can minimize by adjusting the stretching factor, and the third is spectral narrowing caused by the fact that the gain factor of the amplifier medium is wavelength dependent. All these problems have been addressed in numerous variations of the technique, such as spectral filtering, adaptive phase control, or specially designed chirped mirrors, and pulses shorter than 16 fs were achieved.[3–5]

Another idea, which is energetically superior to spectral filtering and was proposed by Danailov and Christov,[6] is to spatially disperse the seed beam inside the gain medium and then to choose the amount of energy to be put into each wavelength component. With this artificial inhomogeneous broadening, the effective gain factor of each wavelength component is determined only through the dedicated pump intensity profile. As a result, gain competition among different wavelength components and redshifting of the spectrum can be eliminated, assuming that the individual wavelength components are truly decoupled from one another inside the gain medium. Although such broadband amplification has been demonstrated, compression has not been achieved.[7]

In this Letter we demonstrate the successful amplification and compression of broadband spectra for the first time to our knowledge and the generation of pulses of 14.8-fs duration with an energy of 450 μJ at a repetition rate of 1 kHz. Amplified spectra currently support transform-limited pulses as short as 14.6 fs; the limiting factor is the spectral bandpass of the dielectric mirrors used in our setup. Furthermore, these experimental findings show excellent agreement with predictions from a numerical simulation.

The setup consists of a Ti:sapphire oscillator, a preamplifier, and a dispersive amplifier. The Kerr-lens mode-locked oscillator (Femtolasers) delivers 11-fs pulses at a repetition rate of 76 MHz. After single-pulse selection down to 1 kHz and subsequent stretching to 200 ps in an all-reflective grating stretcher (1200 lines/mm), the pulses are sent through an acousto-optic programmable dispersive filter (DAZZLER[8]) to compensate in advance for higher-order dispersion before they enter the preamplifier, yielding pulse energies of 200 μJ. With the spectral width reduced to 40 nm FWHM by gain narrowing, the total spectral throughput of the preamplifier is given by the spectral bandpass of the dielectric mirrors (110 nm, centered at 800 nm). The power density in the spectral wings is more than 2 orders of magnitude smaller than it is near the center wavelength. The idea is then that these wings are amplified in the spatially dispersed four-pass amplifier, whereas the central part of the spectrum does not experience any further gain. In the dispersive amplifier setup shown in Fig. 1 the incoming collimated seed beam is sent through a Brewster-cut fused-silica prism (FS), and the angularly dispersed spectral components are mapped into a line of foci inside the Ti:sapphire crystal, which is placed in the Fourier plane. The multipass geometry is chosen such that, after each path, a real image is again created in the focusing plane. After four passes, the angularly dispersed beam is sent through a second prism, hence reversing angular dispersion, before being sent into the grating compressor that comprises two 1200-groove/mm gold-coated diffraction gratings blazed at 600 nm. Depending on the pump's spatial intensity profile, independent amplification of each wavelength component is possible, and gain narrowing can be overcome.

With a pump geometry that employs three independent pump beams (two 2.5 mJ and one 1.2 mJ), each beam is focused to a circular 230-μm spot inside an elliptical seed focus of 200 μm to 1.3 mm (spatially dispersed dimension), which corresponds to a calculated spectral–spatial dispersion of ~1 nm/11.8 μm. Note that the pump beams impose a spatially inhomogeneous thermal load onto the gain medium, which makes proper reversal of angular dispersion difficult and may lead to significant spatial chirp. To

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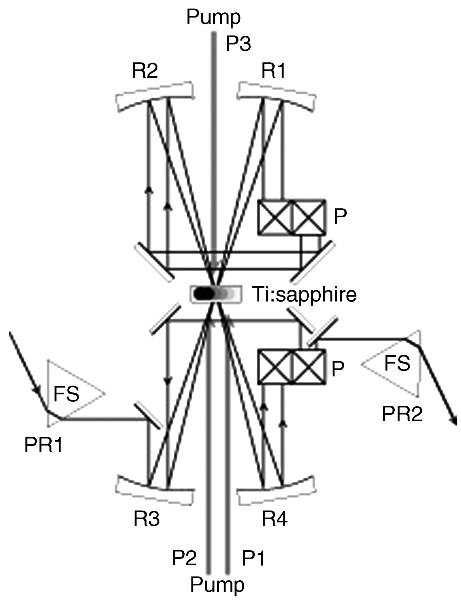

Fig. 1. Experimental setup: R1–R4, focusing mirrors (radii of curvature, 750 mm); Ps, periscope assemblies for mirroring spectral components; Ti:sapphire, crystal with spatially separated spectral components; PR1, PR2, Brewster-cut prisms; P1–P3, pump beams.

circumvent this problem, the crystal is cryogenically cooled to a temperature of 90 K and the number of passes is kept low.

We measured the pulse duration through spectral-phase interferometry for direct electric field reconstruction[9] (SPIDER) and used the DAZZLER filter to compensate manually for higher-order phase distortions. Figure 2 shows the reconstructed temporal pulse shape with a FWHM pulse duration of 14.8 fs [Fig. 2(a)] and the associated spectral phase and spectrum [Fig. 2(b)]. We note that one can easily generate a variety of spectra by simply altering pump beam positions. Beam pointing stability is an important point, and we confirmed, with an on-line single-shot kilohertz SPIDER measurement,[10] that the pointing stability of the seed as well as of the pump (Coherent Corona) did not cause any more than the small fluctuations that are observed in any well-designed amplifier system.

The system employed silver mirrors (altogether 40 reflections), which restricted the obtainable energy to 450 μJ, a value that we expect to increase significantly by using appropriately designed broadband dielectric mirrors. The ratio of amplified spontaneous emission power—without seed—to the power of the amplified signal was less than 1:10.[7] After compression, we measured $M_x{}^2 = 1.6$ and $M_y{}^2 = 1.7$, the latter measured in the dispersed dimension.

The amplification process was numerically modeled, and the results are shown in Fig. 3 for four passes. The simulation, based on the work of LeBlanc,[11] accounts for spatially dependent pumping, nonoverlapping spectral components of the seed and the gain cross section of the Ti:sapphire, modeled according to Eggleston *et al.*[12] We divided the seed spectrum into a number of independent wavelength channels, each of them 0.5 nm wide. The pump spatial profile, matching the seed's spectral spread inside the gain medium, was divided into the same number of channels, so the correct seed energy could be applied to the matching seed channel. We then calculated the gain factor for the successive passes for each channel. Starting from the measured seed and pump parameters [the pump profile is shown in Fig. 3(a)], the successively amplified spectra were as shown in Fig. 3(b). After the first pass through the gain medium (dotted curves) the input spectrum (dashed curve) experienced slightly stronger amplification at shorter wavelengths than, e.g., at 840 nm, where no amplification had been observed until now. During the next three passes, however, the spectrum changed significantly, leading to considerable amplification of the spectral wings. Note that the simulation is in excellent agreement with the experiment, as shown for the simulated spectrum after four passes [Fig. 3(b), solid curves] and the measured spectrum [Fig. 2(b), solid curve].

In conclusion, we have demonstrated, for the first time to our knowledge, direct amplification in a dispersive imaging multipass amplifier and compression to yield 14.8-fs pulses with an energy of 450 μJ at 1 kHz. Our numerical simulation shows excellent agreement with measured parameters, which allows for the reliable prediction of further energy scaling and spectral shaping. With a combination of hollow-fiber compression and subsequent direct dispersive amplification, we expect to overcome the energy limitation of the hollow-fiber approach.

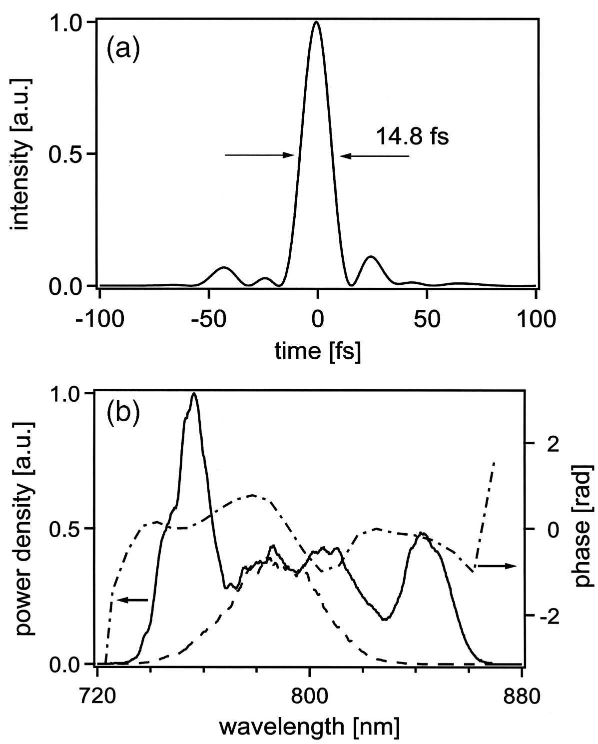

Fig. 2. (a) Reconstructed temporal profile of the amplified pulse. (b) Amplified pulse's spectrum (solid curve) and spectral phase (dashed–dotted curve). The dashed curve shows the spectrum of the preamplified seed pulse.

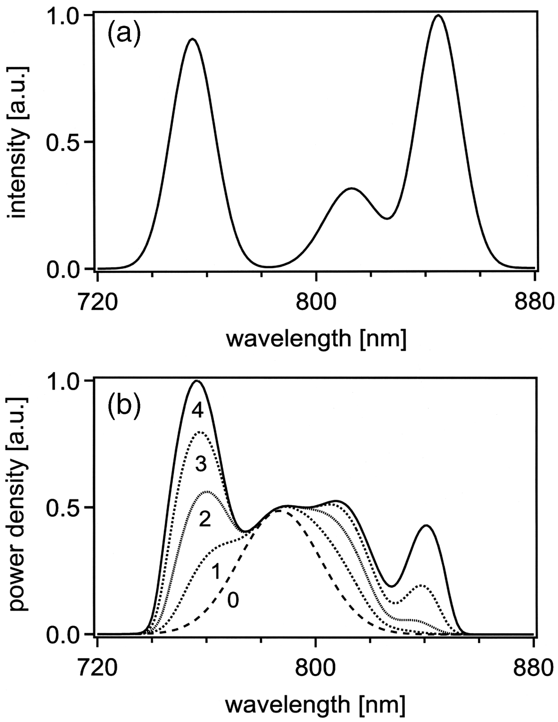

Fig. 3. Amplification modeling: (a) pump intensity profile in the gain medium versus corresponding seed wavelengths; (b) preamplified input spectrum (dashed curve). Predicted spectra for passes 1–3 (dotted curves) and pass 4 (solid curve).

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