Compression of high-energy laser pulses below 5 fs

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High-energy 20-fs pulses generated by a Ti:sapphire laser system were spectrally broadened to more than 250 nm by self-phase modulation in a hollow fiber filled with noble gases and subsequently compressed in a broadband high-throughput dispersive system. Pulses as short as 4.5 fs with energy up to 20-μJ were obtained with krypton, while pulses as short as 5 fs with energy up to 70 μJ were obtained with argon. These pulses are, to our knowledge, the shortest generated to date at multigigawatt peak powers.

Spectral broadening of laser pulses by self-phase modulation (SPM) in a single-mode optical fiber followed by chirp compensation in suitable phase-dispersive elements is a well-established technique for pulse shortening. Pulses down to 6 fs were obtained in 1987 from 50-fs pulses of a mode-locked dye laser,[1] and more recently pulses of ~5 fs were generated from 13-fs pulses of a cavity-dumped Ti:sapphire laser.[2] However, the use of single-mode fibers limits the pulse energy in both cases to a few nanojoules. During the past few years great technological advances have occurred in the field of ultrafast-pulse generation, in particular the development of high-energy solid-state femtosecond lasers. Ti:sapphire amplifiers seeded by 10-fs laser oscillators can now generate pulses of ~20 fs with gigawatt[3,4] or terawatt[5,6] peak power at repetition rates in the kilohertz and 10-Hz regimes, respectively. Recently, a powerful pulse-compression technique based on spectral broadening in a hollow fiber filled with noble gases demonstrated the capability of handling high-energy pulses (submillijoule range).[7] This technique presents the advantages of a guiding element with a large-diameter single mode and of a fast nonlinear medium with a high threshold for multiphoton ionization.

In this Letter we show that combination of the hollow-fiber technique with a broadband, high-throughput dispersive system allows the compression of 20-fs pulses down to a duration as short as 4.5 fs in the pulse-energy range of tens of microjoules, corresponding to multigigawatt peak powers. This result, along with the potential scalability of the system to significantly higher pulse energies, is expected to open up new prospects in high-field light–matter interaction.[8]

We carried out the experiments using a Kerr-lens mode-locked mirror-dispersion-controlled Ti:sapphire oscillator, which provides nearly transform-limited 8-fs pulses.[9] These pulses were amplified at a repetition rate of 1 kHz in a multipass amplifier pumped by the second harmonic of a Q-switched Nd:YLF laser.[3] The output pulses have a duration of 20 fs, energy up to 300 μJ, and a spectrum centered at 780 nm. The pulses were almost transform limited. The amplified pulses were coupled into a 160-μm-diameter, 60-cm-long fused-silica hollow fiber. The fiber was kept straight in a V groove made in an aluminum bar that was placed in a high-pressure chamber with fused-silica windows (1 mm thick) coated for broadband antireflection. The hollow fiber was filled with argon or krypton at different pressures. By properly matching the input beam to the EH_{11} mode of the fiber, we measured an overall fiber transmission of 65%, which is close to the value (~73%) predicted by the theory.[10]

The frequency-broadened pulses emerging from the hollow fiber were compressed by a double pass through two pairs of fused-silica prisms of small apex angle (20°) and by two reflections on a broadband chirped mirror for compensation of quadratic as well as cubic phase distortion. The use of thin prisms with a broadband antireflection coating instead of Brewster-angle prisms allows for a smaller propagation length through glass. This results in a smaller amount of material group delay dispersion and, correspondingly, in a reduction of the negative group delay dispersion required by the prism pairs as well as higher-order dispersion terms. A chirped mirror was introduced to compensate for the cubic phase distortion arising from propagation through the hollow fiber and the prism sequence. This mirror provides at each reflection a negative group delay dispersion with a positive cubic and quartic dispersion. The prism-chirped mirror combination ensures control of second- and third-order dispersion over ~120 THz and provides a high transmission efficiency (>80%) in the range 630–1030 nm.[8]

A typical shape of the spectrum measured at the output of the fiber-compressor system for an argon pressure $p = 3.3$ bars and an input peak power $P_0 = 4$ GW is shown in Fig. 1(a). The shape of the

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