Sub-10-fs mirror-dispersion-controlled Ti:sapphire laser

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We demonstrate the generation of nearly bandwidth-limited 8-fs optical pulses near 0.8 μm from a self-mode-locked Ti:sapphire laser oscillator, using chirped dielectric mirrors for dispersion control. The mode-locking performance is described, and limitations are discussed.

The motivation for generating shorter, more intense, and higher-quality optical pulses comes from many fields in physics and, indirectly, from other areas of science and technology. Optical excitation (and probing) on a time scale of 10^{-14} s provides the only means of creating a coherent macroscopic polarization and investigating important related phenomena in semiconductors[1] as well as studying the dynamics of a number of chemical reactions or biological processes directly in the time domain. On the other hand, the availability of intense optical pulses approximately 10^{-14} s in duration should open the way to reversible nonlinear-optical experiments at intensity levels many orders of magnitude higher than previously feasible in the picosecond and subpicosecond time domains.[2,3]

In this Letter we report on what is to our knowledge the first ultrashort-pulse laser oscillator producing nearly bandwidth-limited optical pulses less than 10 fs in duration. The extremely broad bandwidth necessary to generate electromagnetic energy in such short intervals is provided by Ti-doped sapphire,[4] one of the most excellent broadband laser materials available these days. Exploitation of a substantial part of the enormous bandwidth of Ti:sapphire ($\approx$100 THz) has become possible with the discovery of self-mode locking (also termed Kerr-lens mode locking),[5] a unique method in that a passive amplitude modulation with virtually instantaneous response is introduced without the need for inserting any additional dispersive element in the cavity. Last but not least, femtosecond pulse formation in a broadband solid-state laser relies on a cavity round-trip time decreasing with the optical frequency near the gain line center [negative group-delay dispersion (GDD)] because of the strong self-phase modulation inherent in theses systems. In our self-mode-locked Ti:sapphire laser negative GDD is introduced by the same high-reflectivity dielectric mirrors that provide the feedback necessary for oscillation. These specifically designed chirped multilayer mirrors[6] can produce approximately constant negative GDD over a broader-bandwidth $\Delta\nu_{\mathrm{GDD}}$ than any other low-loss dispersive optical system demonstrated to date.

The finite value of $\Delta\nu_{\mathrm{GDD}}$ has been recognized to be a major effect limiting the performance of practical self-mode-locked oscillators. In systems employing prism pairs for controlling cavity dispersion,[7] third-order dispersion introduced by the prism pair itself was identified as the dominant limitation. Improved performance obtained by use of selected prism materials provided evidence for this finding.[8] The evolution of prism-controlled self-mode-locked Ti:sapphire lasers culminated with the development of a Ti:sapphire oscillator using fused-silica prisms,[9] which were shown to introduce the lowest cubic phase distortion near 0.8 μm among the commercially available optical materials. These systems can now produce pulses in the 10–15-fs region[10–12] but are still limited by the residual cavity third-order dispersion, as evidenced by their pronounced spectral asymmetry.

More recent investigations revealed that the overall cavity third-order dispersion vanishes at $\approx$0.85 μm in a Ti:sapphire laser using fused-silica prisms.[13,14] In fact, extremely broad double-peaked spectra centered at 0.85 μm could be obtained.[14,15] However, the increase in mode-locked bandwidth (beyond 150 nm) was not accompanied by a corresponding reduction in pulse duration because of fourth-order dispersion of the prisms[16] and possible coherent ringing owing to detuning.[17] A careful spectral analysis and fit to the interferometric autocorrelation yielded pulse durations of $\approx$10 fs,[14] whereas 8.5–9-fs pulse durations were evaluated by the simple assumption of a sech^2 pulse shape.[14,15]

In summary, prism-controlled Ti:sapphire lasers are capable of generating high-quality nearly sech^2-shaped pulses with durations as low as $\approx$15 fs. Below 15 fs the spectrum tends to become increasingly asymmetric, and pulse durations near 10 fs can be achieved only at the expense of detuning and a poor pulse quality characterized by time–bandwidth products of $\approx$0.6. In contrast, the mirror-dispersion-controlled (MDC) Ti:sapphire laser presented here delivers 8-fs nearly sech^2-shaped pulses with approximately symmetric spectra and time–bandwidth products of $\approx$0.38.

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