Continuous-wave mode-locked Ti:sapphire laser focusable to 5×10^{13} W/cm^2

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Generation of sub-10-fs pulses with an average power of 1 W and a peak of 1.5 MW from a Kerr-lens mode-locked mirror-dispersion-controlled Ti:sapphire laser is demonstrated. A specially designed lens triplet focuses the output of this compact all-solid-state source to a peak intensity in excess of 5×10^{13} W/cm^2. Nonperturbative nonlinear optics is now becoming feasible by use of the output of a cw mode-locked laser.

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Femtosecond light pulses are important tools for time-resolved spectroscopy and nonlinear optics, owing to their ultrashort duration and high peak power, respectively. Kerr-lens mode-locked Ti:sapphire (Ti:S) lasers[1] employing broadband intracavity dispersion control can now routinely generate pulses of roughly 10 fs or shorter.[2–7] Fused-silica prisms yielded 8.5–10-fs pulses,[2,3] chirped mirrors[8] permitted the generation of 7.5-fs pulses,[6] and the combination of these dispersion-controlling elements recently led to the generation of 6.5-fs pulses[7] from a Ti:S laser. Shorter pulses (≈4.5 fs) could be produced only by external pulse compression.[9,10] Femtosecond Ti:S oscillators delivering pulses in the range extending from a few hundred to a few femtoseconds constitute ideal tools for time-resolved spectroscopy. However, intensities in excess of 10^{12} W/cm^2 were not demonstrated with these systems, limiting their utility for nonlinear optics.

In this Letter we demonstrate that recent innovations in sub-10-fs laser technology now allow generation of sub-10-fs optical pulses at the 1-W average power level with a peak power greater than 1.5 MW and focusing of this output to intensities greater than 5×10^{13} W/cm^2, a range never before reached to our knowledge, at repetition rates of the order of 100 MHz. This performance is achieved with a compact all-solid-state system and opens the way to investigation and possible exploitation of nonperturbative nonlinear optical processes at repetition rates of roughly 100 MHz for what we believe to be the first time. Previously, this domain of nonlinear optics could be reached only by significantly more-complex systems (using, e.g., cavity dumping or external amplification) at lower repetition rates.

Several effects tend to limit the peak power in femtosecond solid-state lasers. The formation of ultrashort pulses in these systems is dominated by a solitonlike interplay[2] between self-phase modulation induced by the Kerr effect in the gain medium and a net negative intracavity group-delay dispersion (GDD) introduced by prisms or chirped mirrors. The separate action of self-phase modulation and negative GDD gives rise to a perturbation that acts periodically on the pulse circulating in the cavity. Variation of the net cavity GDD with wavelength (high-order dispersion) imposes a dispersive perturbation on the solitary pulse. Both effects make the mode-locked pulse shed energy to a quasi-continuum,[11] which coexists with the pulse as a low-intensity background in the laser. This undesirable energy transfer is balanced by self-amplitude modulation (SAM), which tends to suppress the low-intensity background. The periodic and the dispersive perturbations, and hence the related energy-loss rates, rapidly increase for increasing peak intensities and decreasing pulse durations. As a consequence these effects impose severe limitations on the pulse energy achievable in sub-10-fs oscillators. Whereas dispersive perturbations can be effectively minimized by use of chirped mirrors with tailored dispersion,[4–8] keeping periodic perturbations at low levels is more difficult because they are inherent in discrete solitary systems. If the pump power reaches a critical level, scattering to the continuum owing to the discrete action of self-phase modulation cannot be completely balanced by SAM and, as a consequence, a narrow

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spectral feature near 780 nm appears, indicating the coexistence of cw radiation with the mode-locked pulse in the cavity. Increasing the pump power beyond the critical level feeds this undesirable cw background exclusively, and the mode-locked pulse energy remains unchanged. This phenomenon sets a firm limit on the energy of the mode-locked pulse in the current generation of Ti:S oscillators operated in the 10-fs regime.

Recent efforts to attain higher output power from a sub-10-fs Ti:S laser included the use of high output coupling (28%) and a new cooling configuration[12] that allowed efficient transverse heat removal and thus prevented strong temperature quenching[13] from occurring in the laser crystal. When pumped with a frequency-doubled diode-pumped Nd:YVO$_4$ laser (Millennia; Spectra-Physics, Inc.), this system delivered sub-10-fs pulses at an average power of 400 mW.[12] Here we report on further improvements of the oscillator, which yield an average output power of 1 W and, most importantly, focusability of sub-10-fs laser pulses to a spot size comparable with the carrier wavelength for what we believe to be the first time.

Although the basic cavity configuration presented in Ref. 12 was retained, in the experiments described below a new set of chirped mirrors (FemtoSource Pro Mirror Set; FemtoLasers GmbH) exhibiting nearly constant negative GDD over an increased range (≈650 to 950 nm) and an output coupler with 35% transmittivity at 780 nm were employed. Further, the hard aperture was removed because soft-aperture Kerr-lens mode locking was found to provide efficient SAM at this high output coupling. The laser is pumped by a high-power diode-pumped green laser (Millennia-X; Spectra-Physics). The critical pump power was found to be ≈8.5 W (absorbed fraction, ≈70%). Slightly below this value the Ti:S laser delivers highly stable pulses ≈7 fs in duration with an average power of 1 W at a repetition rate of 75 MHz. The corresponding output pulse energy and peak power are 13.3 nJ and 1.56 MW, respectively. The quality of dispersion control provided by the new broadband mirror set is impressively demonstrated by the well-behaved shape of the mode-locked spectrum extending over 300 nm (solid curve, Fig. 1) and the absence of dispersive resonances[2,14] over this range. This performance also shows the capability of the gain-aperture-based Kerr-lens mode locking to produce strong SAM at the high effective saturated gain of ≈0.4.

To assess the focusability of this output, we performed a detailed characterization of the beam delivering the femtosecond pulse train. We gently focused the laser beam with $f/250$ optics to avoid aberrations and measured the transverse intensity distribution with a beam profiler (Model LS-4; Sensor Physics, Inc.) at different positions downstream of the focusing lens. At each position a Gaussian intensity distribution $I(r, z) \propto \exp[-2r^2/w(z)^2]$ was fitted to the measured profile. Figure 2 depicts the evaluated spot size $w(z)$ in the horizontal and the vertical planes. The measured position dependence of $w(z)$ was found to follow the evolution of the spot size in a Gaussian-like beam, $w_i^2(z) = w_{i0}^2 + M_i^4(\lambda^2/\pi^2 w_{i0}^2)(z - z_{0i})^2$, with a divergence that was larger by a factor of M_i^2 than a diffraction-limited Gaussian beam with the same beam waist w_{i0} in the horizontal ($i = x$) and the vertical ($i = y$) planes.[15] Using w_{i0} and M_i^2 as fit parameters and setting $\lambda = \lambda_0 = 780$ nm, we fitted the above expression, as shown by the filled ($i = x$) and the open ($i = y$) circles in Fig. 2. The curves in Fig. 2 depict the least-squares fits yielding $M_x^2 = 1.1$ and $M_y^2 = 1.3$. The assumption of quasi-monochromacity of the laser output is implicit in this evaluation. This is a reasonable approximation, given that ≈90% of the output radiation is delivered within a relative bandwidth of ±7% near 780 nm. Interestingly, spatial coherence in the vertical direction is slightly inferior to that in the horizontal plane. We surmise that this difference relates to the anisotropy in the SAM action in the sagittal and the tangential planes.

The combination of megawatt peak power capability with nearly diffraction-limited performance offers the potential for reaching intensities never before demonstrated with a cw mode-locked laser to our knowledge. To this end we focused the laser output with a custom-designed[16] antireflection-coated triplet (CDHC, China) with a diameter of 4 mm and a focal length of 5.8 mm. The triplet was optimized for minimum chromatic and spherical aberration.[17] The dashed curve in Fig. 1 depicts the variation of the focal length as a function of the wavelength. The radial variation of the focal length was less than 2 μm. The lens was placed at a distance of ≈2 m from the laser output coupler, and its focus was imaged with a second lens of the same type onto a CCD camera. The measured intensity profile at the beam waist that was obtained is

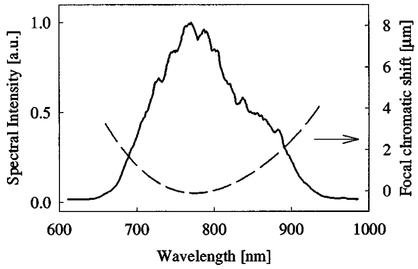

Fig. 1. Mode-locked spectrum of the mirror-dispersion-controlled Ti:S laser (solid curve) and variation of the focal length of the triplet lens used in the experiments versus wavelength (dashed curve).

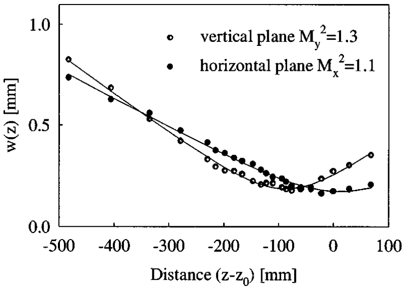

Fig. 2. Variation of the spot size of the output beam near the focus of a low-f-number lens. The curves show Gaussian fits as described in the text.

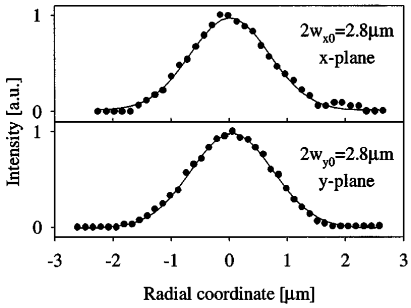

Fig. 3. Intensity profile of the laser beam at the focus of a 5.8-mm-focal length achromatic objective lens.

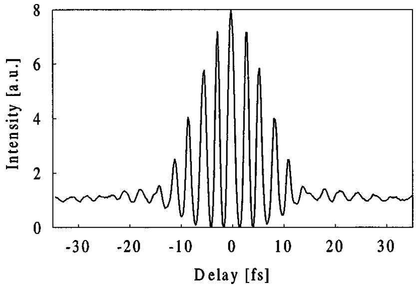

Fig. 4. Interferometric autocorrelation of the focused sub-10-fs laser.

depicted by the filled circles in Fig. 3, along with the respective Gaussian fits. The $1/e^2$-diameter evaluated from these measurements is 2.8 μm. We could eliminate the astigmatism of the laser beam (see Fig. 2) by slightly tilting the triplet held by a precision laser mirror mount. Beam profile measurements were also performed by the knife-edge technique.[18] An opaque knife edge mounted upon a piezo-driven translation stage was scanned across the beam waist (with the laser beam attenuated), and the transmitted power was recorded as a function of the edge position. From this measurement a $1/e^2$-diameter of 2.6 μm was obtained. To measure the minimum achievable pulse duration at focus, we replaced the parabolic mirror in front of the BBO crystal in the autocorrelator with the triplet lens. The GDD introduced by the lens (and the autocorrelator beam splitter) was compensated for by 14 bounces off chirped mirrors similar to those used in the oscillator (total GDD, ≈ -600 fs^2). Figure 4 shows the interferometric autocorrelation signal produced by a 15-μm-thick β-barium borate crystal in the focus of the triplet. The pulse is slightly broadened (to $\approx$8.5 fs), presumably owing to high-order dispersion of the lens material. The low energy contained in the pedestal provides additional evidence for the low spherical and chromatic aberration of the lens. The measured spatial and temporal characteristics of the laser radiation at the focus of the triplet yield a peak intensity exceeding 5×10^{13} W/cm^2.

In conclusion, we have demonstrated an all-solid-state Ti:sapphire laser generating highly stable sub-10-fs pulses with an average power of 1 W in a nearly diffraction-limited beam focusable to a spot size comparable with the wavelength. As a result, peak intensities in excess of 5×10^{13} W/cm^2 could be achieved for what we believe to be the first time directly from a cw mode-locked laser. The research presented here opens the way to the investigation and exploitation of nonperturbative nonlinear optical processes by using cw mode-locked laser oscillators.

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