Femtosecond Ti:sapphire ring laser with a 2-GHz repetition rate and its application in time-resolved spectroscopy

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A Kerr-lens mode-locked femtosecond Ti:sapphire laser operating at a repetition rate of 2 GHz is demonstrated. A mirror-dispersion-controlled unidirectional ring cavity delivers nearly bandwidth-limited pulses of 23-fs length. Mode locking is self-starting without a hard aperture in the cavity. The advantages of this high-repetition-rate oscillator in optical time-resolved spectroscopy are demonstrated. © 1999 Optical Society of America

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The development of femtosecond high-repetition-rate (HRR) lasers with repetition rates in the gigahertz range opens a wide range of applications in femtosecond technology. In optical communication systems these lasers provide the necessary bandwidth for wavelength-division multiplexing of a large number of channels with a single time-division-multiplexed modulator in a combined wavelength-division-multiplexing–time-division-multiplexed technique.[1] The bit rate is set by the laser's repetition rate, making a HRR femtosecond laser highly desirable. In the domain of measuring applications major improvements for time-resolved spectroscopy are expected. HRR lasers allow the reduction of peak intensities while maintaining a high average power, which is important for achieving high signal-to-noise ratios (SNR's). The high repetition rate is accompanied by a compact cavity with a length of less than 20 cm. Compactness is a key issue in the development of a handy all-solid-state femtosecond spectroscopy tool, opening femtosecond technology to broader applications. Key questions in realizing HRR femtosecond lasers are how to realize compact dispersion control and how to maintain mode locking at reduced intracavity peak intensities. Ramaswamy and Fujimoto achieved a 1-GHz repetition rate with a prismatic Ti:sapphire (Ti:S) laser crystal and a prismatic output coupler for dispersion control.[2] The highest repetition rate with a complete mirror-dispersion-controlled resonator of which we are aware was 500 MHz, as demonstrated by Stingl *et al.*[3]

To support solitonlike pulse formation in the cavity one has to compensate for the positive group-delay dispersion (GDD) introduced by the crystal by use of intracavity dispersive elements with negative GDD. The classic solution is an intracavity prism sequence.[4] For sufficient negative GDD an apex distance of typically some 10 cm per prism pair is needed. This requirement makes it difficult to reach repetition rates greater than $\approx$200 MHz. Higher compactness has been achieved with concepts involving the use of a prismatic crystal and output coupler.[2] Gires–Tournois interferometer mirrors can provide negative GDD without restrictions on the minimum optical path length.[5] However, these mirrors are resonant structures and do not yield a flat negative GDD over a wavelength range broad enough to provide pulses significantly shorter than 50 fs. The only dispersive elements that allow short cavities and simultaneously provide a broad (typically 100-nm) constant negative GDD curve are high-reflectivity chirped mirrors.[6] These mirrors permit the generation of sub-50-fs pulses at gigahertz repetition rates.

We report on a unidirectional mode-locked mirror-dispersion-controlled Ti:S ring laser that delivers almost perfectly bandwidth-limited 23-fs pulses. The oscillator works at a repetition rate of 2 GHz. This is to our knowledge the highest repetition rate achieved for a femtosecond-pulse laser with a pulse length significantly shorter than demonstrated in the past at a comparable repetition rate.[2] We use a ring concept similar to that introduced by Pelouch *et al.*,[7] which was already used with dispersive mirrors by Kasper and Witte.[8] The necessary compactness for a HRR laser is achieved with chirped high-reflectivity coatings on all mirrors, including the focusing mirrors, except for the output coupler. We demonstrate performance of a HRR Ti:S ring laser operating at 1 GHz in an optical time-resolved pump-probe experiment that is superior to that of conventional $\approx$100-MHz systems.

A 2.2-mm-long highly doped Ti:S crystal with an absorption coefficient of $\approx 5\ \mathrm{cm}^{-1}$ at 532 nm is mounted at Brewster's angle. A frequency-doubled Nd:YVO$_4$ laser at 3.7-W output power is focused into the crystal with $f = 30$ mm. The astigmatically compensated cavity, illustrated in Fig. 1, consists of chirped focusing mirrors with $f = 15$ mm, three flat chirped mirrors (M1–M3), and an output coupler with 99% reflectivity.

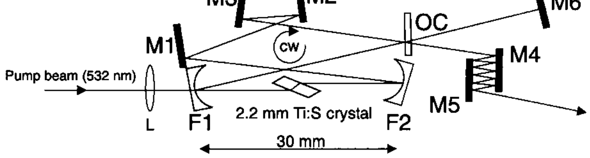

Fig. 1. Cavity design of the 2-GHz mirror-dispersion-controlled Ti:S ring oscillator: L, $f = 30$ mm lens; F1, F2, chirped focusing mirrors with $f = 15$ mm; M1–M5, flat chirped mirrors; OC, 1% output coupler; M6, external mirror.

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The cavity is aligned for maximum bidirectional cw output with a spatial mode close to TEM_{00}. Reducing the distance between mirrors F1 and F2 by moving F2 toward the short edge of the cavity's stability range permits self-starting unidirectional mode locking. Soft-aperture mode locking is not possible at the long-distance edge of the stability range. This result is in agreement with theoretical calculations of the intracavity mode that take into consideration the Kerr nonlinearity according to Ref. 9. Clockwise or counterclockwise mode-locked operation is chosen randomly. Reflecting the counterclockwise-propagating beam back into the cavity with mirror M6 forces the laser to start in the clockwise direction only.

In general, an asymmetric energy distribution between two counterpropagating pulses is advantageous for Kerr-lens mode locking. A stronger Kerr effect, stronger self-phase modulation, shorter pulses, and higher gain modulation for the direction with higher pulse energy are expected under these conditions. Maximum gain modulation through Kerr lensing that interacts with the soft aperture introduced by the spatial gain profile in the crystal is achieved if all the energy is within a single pulse in one of the possible directions. This condition makes unidirectional mode locking the favorable operation mode for a Kerr-lens mode-locked ring laser.

The Ti:S crystal introduces a GDD of $\approx 148\ \mathrm{fs}^2$ into our cavity. We compensate for this by five reflections on chirped mirrors, with a mean GDD of $\approx -45\ \mathrm{fs}^2/\mathrm{reflection}$, resulting in a net GDD of $\approx -77\ \mathrm{fs}^2$ per cavity round trip. The theoretical prediction for the minimum possible pulse duration is then[10]

$$\Delta\tau = 3.53|D|/(\Phi E_P) + \alpha\Phi E_P\,. \tag{1}$$

D is the net cavity GDD, and $\Phi = 2n_2 L_{\mathrm{Kerr}}/\lambda_0 {w_0}^2$ is the nonlinear phase shift per round trip and unit power. $n_2 = 3.2 \times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$ is the nonlinear refractive index of sapphire, $\lambda_0 = 782$ nm is the central wavelength, L_{Kerr} is the length of the Kerr medium, and w_0 is the beam waist in the Kerr medium, calculated with a simple $ABCD$-matrix formalism to be $\approx 17\ \mu\mathrm{m}$. With these values $\Phi = 7.2 \times 10^{-7}\ \mathrm{W}^{-1}$ is calculated. E_P is the intracavity pulse energy, calculated as $E_P = P_{\mathrm{av}}/(T_{\mathrm{OC}} f_{\mathrm{Rep}})$ (where $T_{\mathrm{OC}} = 0.01$ is the transmissivity of the output coupler and $f_{\mathrm{Rep}} = 2$ GHz is the repetition rate). $\alpha\Phi E_P$ ($\alpha \approx 0.1$ for the dispersive end of the cavity) is a correction term that is negligible in our setup (<2 fs). Inserting our achieved average output power of $P_{\mathrm{av}} = 300$ mW into the equation for E_P yields a pulse length of 25 fs.

The GDD of the 5-mm-thick output coupler is externally compensated for by ten bounces of reflections on chirped mirrors. The interferometric autocorrelation measured with an autocorrelator and the mode-locked spectrum are shown in Fig. 2. Assuming sech^2-shaped pulses, the pulse length is 23 fs, in good agreement with the calculation for solitonlike pulse formation in our configuration. The very symmetric spectrum has a FWHM of 28.5 nm around the central wavelength of 782 nm. A time–bandwidth product of $\tau\Delta\nu = 0.322$, which is close to the theoretical limit of 0.315 for sech^2-shaped pulses, is achieved.

It is possible to reduce the pump power to only 1.3 W. Then, the oscillator is not self-starting anymore. Mode locking is initiated by slight knocking on a mirror mount or by vibration of mirror M6, similarly to what was reported in Ref. 8. However, the position of M6 is not a cricital parameter, as reported in Ref. 8. At 1.3-W pump power the pulse length increases to 65 fs at 90-mW output power.

The repetition rate of the laser is measured indirectly by an intensity cross correlation of two successive pulses delivered from the cavity. The distance d between two successive pulses is measured to be 147.614 mm, with an estimated error of 2 μm, resulting in a repetition rate of 2.0303 GHz. The same result is obtained by monitoring of the output of the laser with a fast photodiode on a spectrum analyzer (Tektronix 497P).

The mean M^2 factor of the pulsed output is <1.1. This excellent beam quality is a characteristic feature of the demonstrated cavity, in contrast with other concepts for HRR lasers that inherently produce a spatially chirped output.[2]

Several time-resolved experiments that utilize femtosecond-pulse lasers require low pulse energies. A minimum pulse energy at a given repetition rate is defined by the signal detection limit of the experiment. Provided that there is an appropriate data-acquisition system, the detection limit is set by the shot noise of the detectors, which is proportional to the average photocurrent (optical power).[11] Increasing the repetition rate by a factor K has the consequence that in a given experiment the peak power can be reduced by K while the average power and thus the SNR is maintained. On the other hand, the SNR is increased by K at the maintained pulse energy, since the average power increases by K. Hence HRR pulse lasers are especially favorable in time-resolved spectroscopic experiments that require low peak powers.

Next we demonstrate the potential of our concept for an ultracompact femtosecond spectroscopy tool in a time-resolved electro-optic sampling experiment. Coherent electronic Bloch oscillations (BO's) are excited and monitored in a GaAs–AlGaAs semiconductor

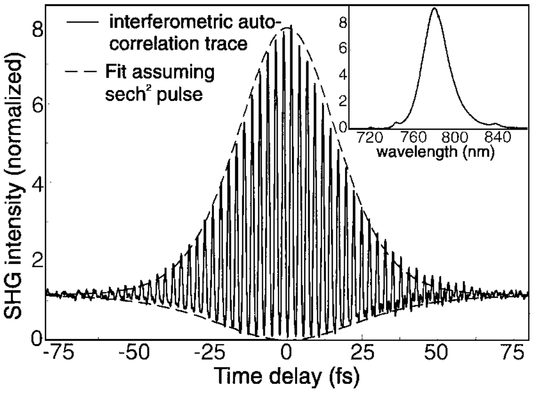

Fig. 2. Interferometric autocorrelation of the compressed 23-fs pulse and a fit assuming a sech^2-shaped pulse. Inset, corresponding spectrum centered around 782 nm. SHG, second-harmonic generation.

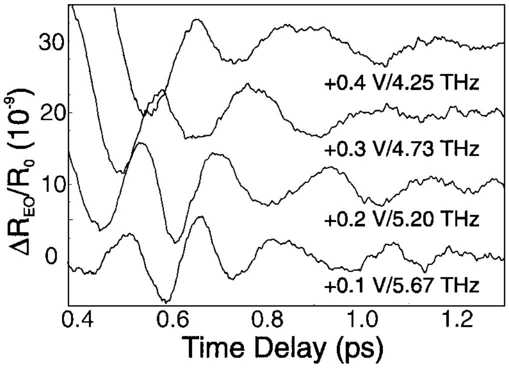

Fig. 3. Time-resolved electro-optic signature of coherent BO's in a semiconductor superlattice measured with a 1-GHz HRR laser for different bias voltages applied to the sample. The BO frequencies obtained from Fourier transformation are indicated by the applied bias voltages.

superlattice. This is a highly challenging task because one has to keep the excited carrier density less than $\approx 10^{16}$ cm^{-3} to reduce carrier–carrier scattering, which is one of the main dephasing channels of electronic coherence.[12] An upper limit for the average power is given by the maximum photocurrent flowing through the biased sample structure. An optimum of lowest pulse energy at maximum possible average power is proved to be met by a 1-GHz oscillator. The same design as that used for the 2-GHz version yields 100-mW output power at 1.7-W pump power, with pulses of 52-fs duration.

The molecular beam epitaxy–grown superlattice sample consists of 35 periods of 5.1-nm GaAs and 1.7-nm $Al_{0.3}Ga_{0.7}As$. The excitation of the biased superlattice at a temperature of 100 K with a short laser pulse of appropriate wavelength produces a coherent superposition of well-defined quantum states. A spatially and temporally oscillating electronic wave packet is created that is accompanied by an internal electronic polarization. The oscillation period is tunable from ≈3 to 13 THz by the external field strength.[13] The oscillating wave packet can be directly monitored through the Pockels effect in a reflective electro-optic sampling setup. The sample's reflectivity difference for light that is polarized along the two main axes of the Pockels tensor normalized to the unperturbed reflectivity is probed by a time-delayed test pulse. This technique provides a direct measure of the internal polarization that is set up by the BO as a function of time delay after excitation. Experimental details for an analogous transmissive electro-optic sampling experiment are given in Ref. 13. Fast-scanning data-acquisition hardware and software are used (Aixscan, GWU Lasertechnik, Erftstadt, Germany). The sample is excited with a pulse energy of 4 pJ, corresponding to an excitation density of $\approx 2 \times 10^{15}$ cm^{-3}. The transient electro-optic reflectivity differences ($\Delta R_{\mathrm{EO}}/R_0$) for four bias voltages applied to the sample are shown in Fig. 3. The increasing oscillation frequency with applied reverse bias demonstrates the observation of coherent BO. The resolution of the experiment allows one to detect relative reflectivity changes $\Delta R/R_0$ as small as 10^{-9}, opening the way to decisive experiments concerning details of coherent electronic dynamics. This unprecedented resolution corresponds to a 2-order-of-magnitude increase in SNR in comparison with pump–probe experiments with ≈100-MHz systems that were limited to relative signal changes of typically $\approx 10^{-7}$.[13] An estimation shows that a 1-order-of-magnitude increase in resolution can be attributed to the repetition rate. Another factor-of-10 increase is due to the reduced noise level of the solid-state pump source compared with the Ar^+ laser that was used in the research reported in Ref. 13 in conjunction with the fast-scanning data acquisition.

In conclusion, we have demonstrated a self-starting femtosecond-pulse Ti:S ring laser with 1- and 2-GHz repetition rates. The 1-GHz oscillator was used to show the superior performance of HRR femtosecond lasers in optical time-resolved spectroscopy compared with that of conventional 100-MHz systems.

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