Broadband 2.12 GHz Ti:sapphire laser compressed to 5.9 femtoseconds using MIIPS

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We report a self-starting prismless femtosecond Ti:sapphire ring laser whose repetition rate has been gradually increased from 1 to 2.12 GHz. A broadband spectrum extending from 650 to 1040 nm, in which 17% of the intracavity power is generated in a single-pass through the crystal, is preserved in spite of the reduction in peak power. An average power of 0.95 W was obtained for 7.5 W of pump power, with very stable operation verified over 22 hours. Pulses from this laser have been fully characterized in spectral phase, and then compressed to 5.9 femtoseconds using multiphoton intrapulse interference phase scan (MIIPS).

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References and links

1. A. Bartels and H. Kurz, “Generation of a broadband continuum by a Ti:sapphire femtosecond oscillator with a 1-GHz repetition rate,” Opt. Lett. **27**, 1839-1841 (2002).
2. A. Bartels, R. Gebs, M. S. Kirchnerm, and S. A. Diddams, “Spectrally resolved optical frequency comb from a self-referenced 5 GHz femtosecond laser,” Opt. Lett. **32**, 2553-2555 (2006).
3. S. T. Cundiff and J. Ye, “Colloquium: Femtosecond optical frequency combs,” Rev. Mod. Phys. **75**, 325-342 (2003)
4. R. Ell, U. Morgner, F. X. Kärtner, J. G. Fujimoto, E. P. Ippen, V. Scheuerm G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, and B. Luther-Davies, “Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser,” Opt. Lett. **26**, 373-375 (2001).
5. T. M. Fortier, A. Bartels, and S. A. Diddams, “Octave-spanning Ti:sapphire laser with a repetition rate >1 GHz for optical frequency measurements and comparisons,” Opt. Lett. **31**, 1011-1013 (2006)
6. G. T. Nogueira and F. C. Cruz, “Efficient 1 GHz Ti:sapphire laser with improved broadband continuum in the infrared,” Opt. Lett. **31**, 2069-2071 (2006).
7. S. A. Diddams, L. Hollberg, and V. Mbele, “Molecular fingerprinting with the resolved modes of a femtosecond laser frequency comb,” Nature **445**, 627-630 (2007).
8. M. J. Thorpe, K. D. Moll, R. J. Jones, B. Safdi, J. Ye, “Broadband Cavity Ringdown Spectroscopy for Sensitive and Molecular Detection,” Science **311**, 1595-1599 (2006)
9. P. M. Paul, E. S. Toma, P. Breger, G. Mullot, F. Augé, Ph. Balcou, H. G. Muller, P. Agostini, “Observation of a Train of Attosecond Pulses from High Harmonic Generation,” Science **292**, 1689 - 1692 (2001).
10. N. Dudovich, D. Oron, and Y. Silberberg, "Single-pulse coherently controlled nonlinear Raman spectroscopy and microscopy," Nature 418, 512-514 (2002).
11. H. Li, D. A. Harris, B. Xu, P. J. Wrzesinski, V. V. Lozovoy, and M. Dantus, "Coherent mode-selective Raman excitation towards standoff detection," Opt. Express **16**, 5499-5504 (2008).
12. M. C. Stowe, F. C. Cruz, A. Marian, and J. Ye, “Coherent population transfer dynamics controlled by pulse accumulation and spectral phase manipulation,” Phys. Rev. Lett. **96**, 153001 (2006).
13. Y. Coello, Vadim V. V. Lozovoy, T. C. Gunaratne, B. Xu, I. Borukhovich, C. Tseng, T. Weinacht, and M. Dantus, “Interference without an interferometer: a different approach to measuring, compressing, and shaping ultrashort laser pulses,” J. Opt. Soc. Am. B **25**, 140-150 (2008).
14. T. M. Fortier, D. J. Jones, and S. T. Cundiff, “Phase stabilization of an octave-spanning Ti:sapphire laser,” Opt. Lett. **28**, 2198-2200 (2003).
15. T. Fuji, A. Unterhuber, V. S. Yakolev, G. Tempea, A. Stingl, F. Krausz, and W. Drexler, ”Generation of smooth, ultra-broadband spectra directly from a prism-less Ti:sapphire laser,” Appl. Phys. B **77**, 125-128 (2003).
16. T. Brabec, Ch. Spielmann, and F. Krausz, “Limits of pulse shortening in solitary lasers,” Opt. Lett. **17**, 748 – 750 (1992).

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17. A. Bartels, T. Dekorsy, and H. Kurz, “Femtosecond Ti:sapphire ring laser with a 2-GHz repetition rate and its application in time-resolved spectroscopy,” Opt. Lett. **24**, 996-998 (1999).
18. B. Xu, Y. Coello, V. V. Lozovoy, D. A. Harris, and M. Dantus, “Pulse shaping of octave spanning femtosecond laser pulses,” Opt. Express **14**, 10939-10944 (2006).
19. B. Xu, Y. Coello, G.T. Nogueira, F. C. Cruz, and M. Dantus, paper in preparation.

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1. Introduction

Femtosecond Ti:sapphire lasers with repetition rates from 1 GHz [1] to 5 GHz [2] have been developed in recent years, particularly as optical frequency combs for use in optical frequency metrology and atomic clocks [3]. In this case both the repetition rate and the pulse-to-pulse (carrier-to-envelope) temporal phase are actively stabilized. Such high repetition rates allow easier identification of longitudinal modes by wavemeters with typical resolutions of 10^{-7}-10^{-8}. It also facilitates heterodyning with the laser to be frequency measured, due to larger power on the individual comb modes. These lasers have also been implemented with broadband spectra, sometimes even covering one octave [4], which allows stabilization of the pulse-to-pulse temporal phase without need for spectral expansion in microstructured photonic fibers. This is advantageous for long-term operation [5], since the supercontinuum spectrum from the fiber may fluctuate. A large portion of the broadband spectrum is achieved by nonlinear generation in a single-pass through the crystal. In ref. [6] we have demonstrated that this can account for 75% (17%) of the output (intracavity) power.

Other uses for broadband femtosecond lasers include high-resolution molecular spectroscopy [7, 8], optical coherence tomography, holography, TeraHertz generation, high harmonic generation [9], and biophotonic applications such as microscopy based on two-photon fluorescence or coherent anti-Stokes Raman spectroscopy (CARS) [10,11]. In atomic or molecular high resolution spectroscopy carried out with optical frequency combs, the high repetition rate would allow to explore the coherent accumulation effect [12] for fast decaying transitions.

Mode-locking is based on the nonlinear passive mechanism of Kerr lensing and the broadband spectrum (such as in ref [6]), generated in a single-pass through the crystal, is based mainly on self-phase modulation and other nonlinear mechanisms. Therefore one goal of the present work was to investigate whether both mechanisms would maintain the laser operation and broadband generation as the pulse energy is reduced with the increase in repetition rate, of course keeping the same average power. Although recent results demonstrates operation of a similar laser at repetition rates up to 5 GHz [2], the generation of a broadband spectrum directly from an oscillator operating at a repetition rate higher than 1 GHz is still not demonstrated.

In this paper we describe a self-starting, broadband femtosecond Ti:sapphire ring laser operating at repetition rates from 1 GHz to 2.12 GHz. We compare the spectra obtained for three different sets of mirrors, which expand beyond the laser cavity and gain bandwidths. The complex pulses generated by this laser are difficult to characterize with conventional techniques due to the broadband spectra. Nevertheless, we have measured and corrected the spectral phase, recompressing the pulses to 5.9 fs (near the Fourier-transform limit) using multiphoton intrapulse interference phase scan (MIIPS) [13]. We achieved what seems to be the laser with the shortest pulses and highest repetition rate reported so far. On going work for stabilization of the carrier-to-envelope phase should allow for a unique laser source combining ultrashort pulses, high repetition rate, and controllable spectral and temporal phases.

2. Laser description and results

Figure 1 shows a diagram of the Ti:sapphire laser cavity. It is the same ring cavity reported in Ref. [6], whose dimensions have been gradually reduced (15 steps) until a repetition rate of 2.12 GHz has been obtained. The repetition rate has been measured with a fast photodetetor and a spectrum analyzer. We did not attempt to increase this rate further because of size limitations of our optomechanical components. It is therefore possible that a broadband spectrum could be maintained for higher rates. All the mirrors (two curved 3-cm ROC near the crystal, one convex mirror and one flat mirror) are chirped, except the output coupler (2% transmitting). As shown in Fig. 1, when pumped by a single-frequency laser at 532 nm (Coherent Verdi), the laser emits up to 970 mW for 7.3 W of pump power. The angles on the curved mirrors are such to compensate for astigmatism. The laser is self-starting, runs in only one of the oscillation directions depending on the position of the crystal and the pump lens focus, and is extremely stable in mode-locked regime. In a recent experiment it was operated continuously for 22 hours.

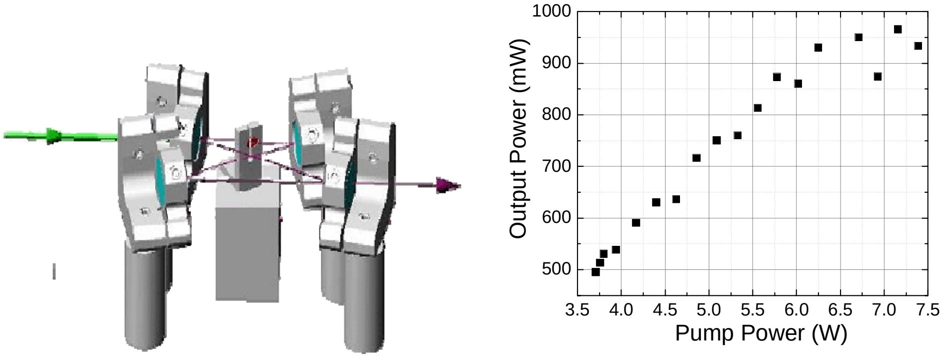

Fig 1. Left: Diagram of the prismless short ring laser cavity operating at 2.12 GHz. The two mirrors adjacent to the 3 mm-long crystal are curved (3 cm ROC) and the length between the other flat mirrors is 3 cm. Right: Laser output power as function of the pump power at 532 nm.

Figure 2 shows the spectra of the 2.12 GHz laser obtained with three different sets of chirped mirrors. The first set (black curves in Figs. 2(a) and 2(b)) is the same used in our previous work [6]. It consists of two curved chirped mirrors (ROC= 3 cm) and a convex (ROC = -1 m) chirped mirror. The output coupler (OC) is not chirped and has very small GDD [6]. The calculated GDD curves of the chirped mirror, provided by the manufacturer, combined with the flat positive Ti:sapphire GDD of 174 fs^2 gives the net GDD curve shown in Fig. 2(a) (black dashed curve). The net GDD has been measured also by white light interferometry [6]. This curve shows a few oscillations around zero, with an average value of only -3.5 fs^2 from 700 to 900 nm. The corresponding spectrum (black solid curve) shows that the same performance obtained at 1 GHz could be maintained up to 2.12 GHz, when the pulse energy is reduced to more than one half. As determined for the 1 GHz repetition rate [6], 17 % of the intracavity power is generated outside the cavity bandwidth (defined from 700 to 900 nm, where the OC reflectivity drops to 20%) by nonlinear generation in a single pass through the crystal. Because of the 2% transmission of the OC, this fraction amounts to 75 % on the output power [6].

In the second set of mirrors (red curves in Fig. 2), the input coupler was replaced by another chirped mirror, leading to the net GDD curve shown in Fig. 2(a) (dashed red curve). The GDD oscillations are reduced, but the curve still looks similar to the previous set. The corresponding spectrum (red solid curve, Fig. 2) is also similar to the previous one (black).

In the third set of mirrors, the second curved mirror has been replaced by another, whose GDD oscillations compensate the ones from the input coupler (IC) (compensated pair; blue dashed curve in Fig. 2). We see that the peak at 680 nm was greatly reduced, while the power around 780 nm and 1000 nm increased. Similar strong peaks near 700 nm have been observed in broadband Ti:sapphire lasers in Refs. [1], [5], [14], and [15]. In Ref. [15] this peak was reduced only after compensation of third-order dispersion which, according to the authors, was more important than compensation of GDD oscillations for obtaining a smooth spectrum. In our case, all three set of mirrors have similar GDD below 720 nm, and the reduction of this peak appears to be related to the reduction of GDD oscillations. For this same set of mirrors, we were also able to obtain a much smoother spectrum, as we describe later.

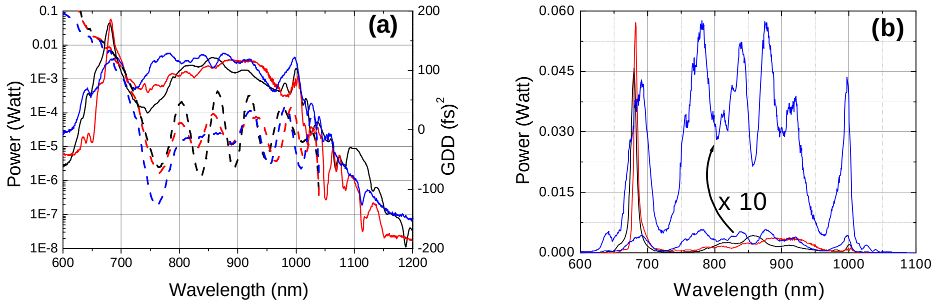

Fig. 2. (a). Laser spectra (solid) and corresponding net GDD curves (dash) for the three mirror sets used in this work. Black: same set used in reference [6]; Red: the input coupler was replaced by another chirped mirror; Blue: the second curved mirror was replaced by another whose GDD oscillations compensate the ones from the IC. (b) Laser spectra of Fig. (a) in linear scale. Note that the peak at 680 nm is greatly suppressed (blue curve, 3rd set of mirrors).

Based on the net cavity GDD, an estimation of the minimum pulse duration can be obtained for our laser, using an empirical formula obtained in Ref. [16]:

$$\Delta t = 3.53|D|/(\Phi E_P) + \alpha\Phi E_P \qquad (1)$$

The underlying model includes self-phase modulation (SPM), GDD, passive amplitude modulation (PAM), gain dispersion, and third order dispersion (TOD) [16]. In Eq. (1), D is the net cavity GDD (estimated from [6] as -3.5 fs^2 (average) from 700 to 900 nm), and $\Phi = 2n_2L_{\mathrm{Kerr}}/\lambda_0 w_0^2$ is the nonlinear phase shift per round trip and unit power, where $n_2 = 3.2\mathrm{x}\ 10^{-20}$ m^2/W is the nonlinear refractive index of sapphire, λ_0 = 782 nm is the central wavelength, L_{Kerr} is the length of the Kerr medium (3 mm), and w_0 is the beam waist in the Kerr medium. It was calculated from an *ABCD*-matrix formalism to be ≈ 42 µm at the border of the stability region of the cavity, where mode-locked operation happens. Using these values we obtain Φ = 1.39 x 10^{-7} W^{-1}. The intracavity pulse energy is calculated as 23 nJ from $E_P = P_{\mathrm{av}}/(T_{\mathrm{OC}}f_{\mathrm{Rep}})$ (P_{av} = 900 mW is the average output power, T_{OC} = 0.02 is the transmissivity of the output coupler and f_{rep} = 2.12 GHz is the repetition rate). From these we obtain ΦE_p = 3.13 fs. The first term in Eq. (1) gives only 3.9 fs. The second term, $\alpha\Phi E_{P,}$ is a correction factor that is not negligible in our case, resulting in 0.31 fsec for α = 0.1 for the dispersive end of the cavity (α is a numerical factor depending on the position where Δt is measured in the cavity) [16]. The minimum pulse duration would therefore be 4.3 fs. Similar minimum pulse durations can also be obtained as the Fourier-transform limit of the spectra of Fig. 2. The estimation from Eq. (1), however, indicates that the short pulse results mainly from the small net GDD of the cavity, since the nonlinear phase ϕ is only 1.7 times the one of a 2 GHz laser of ref. [17] and smaller than that reported for a 5 GHz laser [2].

3. Spectral phase characterization and correction with MIIPS

We have characterized the spectral phase of the 2.12 GHz laser using MIIPS [13]. The experimental setup is described in Ref. [18]. Briefly, MIIPS is a single beam pulse measurement and phase compensation method that does not depend on any type of autocorrelation. The measurements are achieved using a pulse shaper (640 pixel phase amplitude modulator) at the Fourier plane which introduces a series of reference phase functions of the form $f(\omega,\delta)=\alpha\sin[\gamma(\omega-\omega_0)-\delta]$ with α and γ as fixed parameters and δ as a parameter that scans over a 4π range. The second harmonic spectra, collected after each of the reference functions is introduced, collectively provide the MIIPS traces, as shown in Fig. 3. From the MIIPS trace it is possible to obtain the spectral phase distortions of the pulses. This information is used to design a phase compensation function that is introduced to cancel the measured distortions. When the distortions are very large, as in this case where they span almost 100 rad across the spectrum, a number of phase compensation iterations are required to achieve transform-limited pulses. One of the reasons why MIIPS is a very robust measurement method is that transform-limited pulses are characterized by parallel features separated by π, as shown in Fig. 3(b). Reference [13] shows a comparison of measurements performed by MIIPS, interferometric autocorrelation, and interferometric FROG, and several demonstrations of MIIPS precision and accuracy, including compression of ~4fs pulses evidenced by the generation of a ~200nm bandwidth SHG spectrum, chromatic dispersion measurements of optical media with ±0.2fs^2/mm accuracy, and measurements of arbitrarily complex spectral phases.

The measurements of Fig. 3 were performed on the laser with a smoother spectrum shown in Fig. 4(a), obtained by changes in the alignment. This spectrum covers 328 nm, defined between the points in which the intensity decreases to 25% (6 dB) from the peak. The insertion loss of the MIIPS setup was 40%.

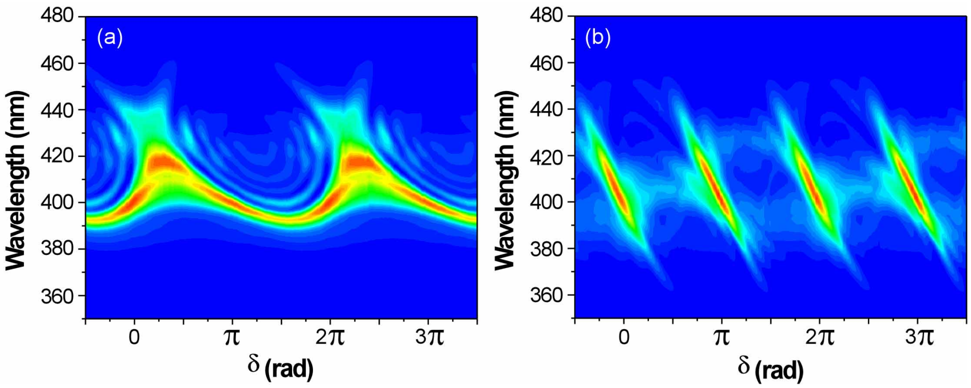

Fig. 3. MIIPS traces of the first (a) and last (b) iterations. Each vertical line of the MIIPS trace corresponds to a SHG spectrum generated at given value of δ (redder colors represent higher intensities). For transform-limited pulses (b), the features form parallel lines separated by π.

In Fig. 4(a), we show the spectrum of the pulse and the measured phase distortions. The inset shows the remaining phase distortions after MIIPS, with a maximum deviation of less than 0.2 rad across the bandwidth of the pulse. From the measured phase function we can extract the GDD and TOD values of the laser output, which are ~0 fs^2 and ~3300 fs^3 for 800 nm, respectively. From the residual phase and the spectrum, the calculated FWHM pulse duration is 5.9 fs, as shown in Fig. 4(b). The broad SHG spectrum after MIIPS compression shown in Fig. 4(b) confirms that spectral phase distortion was corrected.

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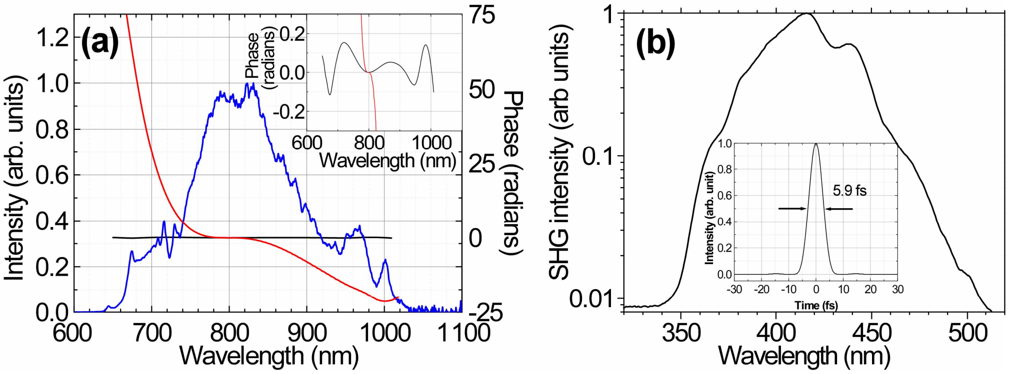

Fig. 4. (a). Blue: Spectrum of the 2.12 GHz laser covering 328 nm (from 674 to 1002 nm, at 25% from the peak), obtained with third set of mirrors; red: spectral phase before correction; black: spectral phase after correction, and in expanded view on the inset. (b). SHG spectrum corresponding to the phase corrected pulses. Inset shows the calculated temporal profile after compression by MIIPS.

This laser system can also be applied in rapid and encrypted telecommunication, exploiting the broad spectrum at high repetition rate of the oscillator and the fact that different binary phases result in unique nonlinear spectra (e.g SHG spectra). A set of experiments was carried out and demonstrated that the current system can carry 64-bit encrypted information. Details of these experiments will be presented elsewhere [19].

4. Conclusion

We report a compact, broadband, self-starting prismless femtosecond Ti:sapphire ring laser operating with repetition rates from 1 to 2.12 GHz. Powers of 0.95 W (0.8W) have been obtained for 7.5 W (5 W) of pump power at 532 nm, with very stable continuous operation verified over 22 hours. Broadband emission, which is strongly dependent of nonlinear effects, was preserved in spite of the reduction in peak power as the repetition rate is increased. We compare spectra obtained for three sets of mirrors. Smoother spectra covering 328 nm (at 25% of the peak) and beyond the laser cavity bandwidth, have been obtained by reducing GDD oscillations. The spectral phase of the 2.12 GHz laser pulses has been fully characterized using multiphoton intrapulse interference phase scan (MIIPS) and has then been compensated to yield near transform-limited pulses with durations of 5.9 fs. We thus achieved what seems to be the laser with the highest repetition rate and shortest pulses reported so far. On going work for stabilization of the carrier-to-envelope offset frequency should allow for a unique laser source combining ultrashort pulses, high repetition rate, and controllable spectral and temporal phases.

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