Spectrally resolved optical frequency comb from a self-referenced 5 GHz femtosecond laser

A. Bartels, R. Gebs
Gigaoptics GmbH, Blarerstrasse 56, 78462 Konstanz, Germany and
University of Konstanz, Universitätsstrasse 10, 78457 Konstanz, Germany
bartels@gigaoptics.com

M. Kirchner, and S.A. Diddams
National Institute of Standards and Technology, 325 Broadway M.S. 847, Boulder, CO 80305, USA

We report a mode-locked Ti:sapphire femtosecond laser with 5GHz repetition rate. Spectral broadening of the 24fs pulses in a microstructured fiber yields an octave-spanning spectrum and permits self-referencing and active stabilization of the emitted femtosecond laser frequency comb (FLFC). The individual modes of the 5GHz FLFC are resolved with a high-resolution spectrometer based on a virtually imaged phased array (VIPA) spectral disperser. Isolation of single comb elements at a microwatt average power level is demonstrated. The combination of the high-power, frequency-stabilized 5GHz laser and the straightforward resolution of its many modes will benefit applications in direct frequency comb spectroscopy. Additionally, such a stabilized FLFC should serve as a useful tool for direct mode-by-mode Fourier synthesis of arbitrary optical waveforms. © 2008 Optical Society of America

OCIS codes: 140.7090,120.3940,320.7160

Basic and applied research in the fields of optical frequency metrology,\(^1\) direct frequency comb spectroscopy,\(^2,3\) low-noise microwave generation,\(^4\) and arbitrary waveform generation\(^5\) all benefit from the large mode spacing and high power per mode available from stabilized femtosecond laser frequency combs (FLFC) operating at GHz repetition rates. Indeed, most frequency comb applications benefit from the highest repetition rate within the available photodetector bandwidth for which an octave-spanning spectrum appropriate for self-referencing can be achieved. Optical frequency metrology and direct frequency comb spectroscopy specifically take advantage of the high power per mode since in a typical experiment only the power contained in a few comb teeth contribute to the measured signal, while the other teeth within the detected optical bandwidth add

\(^1\)contribution of an agency of the US government, not subject to copyright
to the measurement noise. Thus, a higher repetition rate intrinsically permits a higher signal-to-noise ratio (S/N). Arbitrary waveform generation experiments aimed at individually addressing the FLFC elements in amplitude and phase via spatial light modulators benefit because a larger mode spacing reduces the required resolving power for the spectral disperser.

Towards this goal, fundamentally modelocked femtosecond lasers with repetition rates up to 4 GHz have been demonstrated.\(^6\),\(^7\) However, the highest reported repetition rate for a fundamentally modelocked and self-referenced FLFC is 1.4 GHz,\(^8\) with the maximum repetition rate ultimately limited by the pulse energy required to achieve sufficient optical bandwidth for self-referencing. Harmonically modelocked femtosecond and picosecond sources with repetition rates as high as 10 GHz and fundamentally modelocked picosecond lasers with up to 77 GHz repetition rate have been demonstrated.\(^9\)–\(^12\) However, self-referencing of such sources could not yet be demonstrated, thus precluding their application for precision spectroscopy. In addition, harmonically modelocked sources exhibit residual modes at the fundamental cavity frequency\(^10\) posing a limit to the obtainable modulation contrast in optical arbitrary waveform generation experiments.

Here, we report a mode-locked femtosecond Ti:sapphire laser producing 24 fs pulses at a 5 GHz repetition rate. Octave-spanning spectra are produced via spectral broadening in a small-core microstructured optical fiber, thus enabling the system to be self-referenced and frequency stabilized. Moreover, the 5 GHz mode spacing is sufficiently large to enable the individual modes to be spectrally and spatially separated and recorded in an efficient two-dimensional format. Direct access to numerous individual comb modes in a parallel architecture provides unique capabilities for novel high-resolution spectroscopic techniques\(^13\) as well as the possibility to precisely control the amplitude and phase of individual comb modes for the generation of arbitrary optical and microwave waveforms.\(^5\) The combination of the 5 GHz comb demonstrated here with line-by-line pulse shaping techniques should ultimately enable the generation of user-designed optical waveforms that possess the femtosecond timing jitter available from well-stabilized optical frequency combs.\(^14\)

The laser cavity is based on a ring design previously used for repetition rates up to 2 GHz (see Fig. 1 for schematic).\(^6\) The 1.5 mm long Ti:sapphire crystal is pumped by 7.5 W from a 532 nm laser through a 30 mm focal length lens and mirror M1. The focusing mirrors M1 and M2 next to the laser crystal have a radius of curvature of 15 mm. The ring cavity is completed by mirror M3 and the output coupler OC. The cavity length is 6 cm, yielding a repetition rate of 5 GHz. Mirrors M1-3 have a high-reflective negative dispersive coating with approximately -40 fs\(^2\) group-delay dispersion (GDD) between 750 nm and 850 nm. Together with the laser crystal contribution, the net cavity GDD is thus approximately -35 fs\(^2\). The output coupler has 2% transmission. To initiate mode-locking, mirror M2 is brought close to the inner edge of the cavity stability range and a slight perturbation is imposed on the cavity (e.g. tapping on a mirror). When mode-locked, the laser operates unidirectionally in a random direction and yields 1.15 W of output power. We choose the operating direction as indicated in Fig. 1. An interferometric autocorrelation trace of the pulses is shown in Fig. 1a. The full-width at half-maximum (FWHM) of the low-pass filtered trace is 36 fs corresponding to a pulse duration of 24 fs under the assumption of a sech\(^2\) pulse envelope. The output spectrum is shown in Fig. 1b and has a FWHM of 35 nm centered around 798 nm. The 5
GHz repetition rate is detected by focusing \( \sim 20 \text{ mW} \) of optical power onto a high-speed GaAs-pin photodiode. The electrical power contained in the 5 GHz signal amounts to -5.7 dBm (into a 50 \( \Omega \) load) with a direct current of \( \sim 5 \text{ mA} \). This signal is used in a phase-locked loop to stabilize the repetition rate to an external hydrogen maser referenced RF-signal at 5.000994 GHz by controlling the cavity length via a piezo crystal that supports mirror M3.

The carrier-envelope offset frequency \( f_0 \) of the laser is measured in an f-2f nonlinear interferometer.\(^{15} \) 950 mW of the output power is launched into a microstructured fiber (1.5 \( \mu \text{m} \) core, zero-GDD wavelength at 590 nm) with an efficiency of 35\%. The optical output spectrum is shown in Fig. 1b. A beat signal between the frequency-doubled light at 1000 nm and the fundamental light at 500 nm is detected with a Si pin photodiode (see Fig. 2a). The bandwidth of the photodiode was approximately 3 GHz, thus the peaks at \( f_R \) and \( f_R - f_0 \) are partly suppressed. \( f_0 \) is stabilized at 250 MHz by controlling the 532 nm pump power via an acousto-optic modulator. The stabilized \( f_0 \) spectrum is shown in Fig. 2b. Residual frequency deviations of \( f_0 \) have been measured using a high-resolution counter and amount to 6 mHz at 1 s gate time.

Approximately 120 mW of the laser output were split off before the microstructured fiber and dispersed in a high-resolution spectrometer that consists of a virtually imaged phased array (VIPA) spectral disperser orthogonally combined with a conventional diffraction grating.\(^{13,16,17} \) The VIPA etalon has a high-reflective coating on the front face (except for an uncoated entrance window) and a 96\% reflectance coating for 800 nm on the output face. The diffraction grating has 1800 lines/mm. The spectrally dispersed elements of the frequency comb are imaged to a first focal plane where the spatially separated FLFC components may be individually manipulated with appropriate devices, e.g. a spatial light modulator (SLM). The spectrometer output is then imaged to a second plane and recorded with a CCD camera. Figs. 3(a) and (b) show a portion of the optical spectrum in the second focal plane with nothing placed in the first focal plane. The individual modes of the 5 GHz frequency comb are well resolved as dots. Vertical neighbors within the optical frequency `brush` are spaced by one repetition rate, horizontal neighbors are spaced by one free spectral range (FSR) of the VIPA spectral disperser (\( \sim 50 \text{ GHz} \)). The spacing of the dots is \( \sim 90 \mu \text{m} \) in the vertical direction and \( \sim 60 \mu \text{m} \) in the horizontal direction. These values are well-suited for spectroscopic detection\(^{13} \) and manipulation of individual FLFC components using two-dimensional SLMs. Here we perform a simpler proof-of-principle experiment by isolating a single frequency comb mode using a 50 \( \mu \text{m} \) diameter pinhole in the first focal plane. Fig. 3(c) shows a view of a single isolated mode at around 802.5 nm wavelength from the center region of the spectrometer output. A power measurement behind the pinhole shows that the isolated mode contains 2.2 \( \mu \text{W} \) of average power.

We have isolated a series of different modes by scanning the pinhole across the dot pattern as indicated in Fig. 3(b). The isolated light has been coupled into a single mode fiber and analyzed with a high resolution (7 GHz) optical spectrum analyzer (OSA). The spectra of the isolated dots number 1 and 2 (spaced by one repetition rate) are shown in the inset of Fig. 3. Crosstalk from modes that are spaced by one or more horizontal spacings (i.e. by multiples of the FSR of the VIPA disperser) is suppressed by more than 20 dB. Crosstalk from modes that are spaced by one or more vertical spacings (i.e. by multiples of \( f_R \)) cannot be resolved by the spectrometer. It is
expected that this crosstalk is significantly below 20 dB because the vertical spatial mode spacing is \( \sim 1.5 \) times greater than the horizontal spacing. The center frequencies of the individual modes are extracted from the OSA measurement and plotted versus mode number in Fig. 4. A linear fit to the data yields a value of 5.09 GHz per mode in good agreement with the stabilized value of 5.000994 GHz within the error that is given by the frequency repeatability of the OSA (2.3 GHz in 1 minute). It should be noted that the specified accuracy of the OSA is only 50 GHz, i.e. the absolute values given in Fig. 4 have a common error of this size that is not indicated in the figure.

A major consideration towards even higher repetition rates is the nonlinear round-trip phase shift \( \Phi_{RT} \) experienced by the pulses in the Ti:sapphire crystal.\(^\text{18} \) The minimum demonstrated \( \Phi_{RT} \) for stable operation of a similar laser was about 50 mrad.\(^\text{6} \) Here, we estimate \( \Phi_{RT} \approx 200 \) mrad. Thus, repetition rates well above 5 GHz should be possible with the presented design. We succeeded in shortening the cavity to yield 6 GHz repetition rate with no significant changes to the output characteristics (see Fig. 2 for an RF spectrum of the repetition rate signal). To our knowledge, this is the highest repetition rate ever demonstrated for a fundamentally modelocked femtosecond laser. Mechanical constraints prevented higher repetition rates. We anticipate that it is straightforward to scale the presented resonator to at least 10 GHz.

In conclusion we have demonstrated a femtosecond laser with 5 GHz repetition rate that can be stabilized in both repetition rate and carrier-envelope offset frequency. We are able to spectrally resolve the emitted FLFC with a VIPA spectral disperser and to isolate individual elements at a microwatt power level. Optical frequency metrology, direct frequency comb spectroscopy and line-by-line pulse shaping will benefit from these experiments.

We thank Andrew Weiner and Leo Hollberg for their vital contributions to this work and acknowledge thoughtful comments on this manuscript provided by Tara Fortier and Jason Stalnaker.

References

1. Th. Udem, R. Holzwarth, and T.W. Hänsch, Nature 416, 233 (2002).
2. A. Marian, M.C. Stowe, J.R. Lawall, D. Felinto, and J. Ye, Phys. Science 360, 2063 (2004).
3. V. Gerginov, C.E. Tanner, S.A. Diddams, A. Bartels, and L. Hollberg, Opt. Lett. 30, 1734 (2005).
4. A. Bartels, S.A. Diddams, C.W. Oates, G. Wilpers, J.C. Bergquist, W.H. Oskay, and L. Hollberg, Opt. Lett. 30, 667 (2005).
5. Z. Jiang, D.E. Leaird, and A.M. Weiner, Opt. Exp. 13, 10431 (2005).
6. A. Bartels, T. Dekorsy, and H. Kurz, Opt. Lett. 24, 996 (1999).
7. C.G. Leburn, A.A. Lagatsky, C.T.A Brown, and W. Sibbett, Electron. Lett. 40, 804 (2004).
8. T.M. Fortier, A. Bartels, and S.A. Diddams, Opt. Lett. 31, 1011 (2006).
9. K.R. Tamura and M. Nakazawa, Opt. Lett. 26, 762 (2001).
10. F. Quinlan, S. Gee, S. Ozharar, and P.J. Delfyett, Opt. Lett. 31, 2870 (2006).
11. B.C. Collings, K. Bergman, and W.H. Knox, Opt. Lett. 23, 123 (1998).
12. S.C. Zeller, T. Südmeyer, K.J. Weingarten, and U. Keller, Electron. Lett. 43, 32 (2007).
13. S.A. Diddams, L. Hollberg, V. Mbele, Nature 445, 627 (2007).
14. A. Bartels, S.A. Diddams, T.M. Ramond, and L. Hollberg, Opt. Lett. 28, 663 (2003).
15. D.J. Jones, S.A. Diddams, J.K. Ranka, A.J. Stentz, R.S. Windeler, J.L. Hall, and S.T: Cundiff, Science 288, 635 (2000).
16. S. Xiao and A.M. Weiner, Opt. Expr. 12, 2895 (2004).
17. S. Xiao and A.M. Weiner, Opt. Expr. 14, 3073 (2006).
18. T. Brabec, Th. Spielmann, and F. Krausz, Opt. Lett. 17, 748 (1992).
Fig. 1. (a) Interferometric autocorrelation trace (solid line) of the 5 GHz pulse train and the low-pass filtered trace (dashed line). Inset: Cavity schematic of the laser. (b) Laser output spectrum scaled in units of power per 5 GHz mode (dashed line) and octave-spanning spectrum after broadening in microstructured optical fiber (solid line).
Fig. 2. (a) Self-referencing beat signal of the 5 GHz laser showing the carrier-envelope offset frequency $f_0$ and the repetition rate $f_R$. The resolution bandwidth (RBW) is 300 kHz. (b) Phase-locked $f_0$ signal with RBW set to 100 Hz. (c) Photodetected 6 GHz repetition rate signal (RBW is 30 kHz).
Fig. 3. (a) Output of the VIPA spectral disperser recorded with a CCD camera. The image covers ∼5 nm of the spectrum centered around 802.5 nm. (b) Zoom into the CCD image. Successive modes of the FLFC are numbered. (c) Mode number 1 isolated with a pinhole.
Fig. 4. Frequency of the isolated FLFC modes versus mode number. Error bars represent the frequency repeatability of the OSA. The line represents the expected dependence for the 5.000994 GHz repetition rate. Inset: Spectra of modes number 1 (solid line) and 2 (dashed line).
Figure 1, A. Bartels et al.
Figure 2, A. Bartels et al.
Figure 3, A. Bartels et al.
Figure 4, A. Bartels et al.