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

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We report a mode-locked Ti:sapphire femtosecond laser with 5 GHz repetition rate. Spectral broadening of the 24 fs 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 5 GHz FLFC are resolved with a high-resolution spectrometer based on a virtually imaged phased array spectral disperser. Isolation of single comb elements at a microwatt average power level is demonstrated. The combination of the high-power, frequency-stabilized 5 GHz 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 optical waveforms.
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Basic and applied research in the fields of optical frequency metrology [1], direct frequency comb spectroscopy [2,3], low-noise microwave generation [4], and waveform generation [5] all benefit from the large mode spacing and high power per mode available from stabilized femtosecond laser frequency combs (FLFCs) operating at gigahertz 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 contributes to the measured signal, while the other teeth within the detected optical bandwidth add to the measurement noise. Thus, a higher repetition rate intrinsically permits a higher signal-to-noise (S/N) ratio. Optical 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.

Toward this goal, fundamentally mode-locked femtosecond lasers with repetition rates up to 4 GHz have been demonstrated [6,7]. However, the highest reported repetition rate for a fundamentally mode-locked 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 mode-locked femtosecond and picosecond sources with repetition rates as high as 10 GHz and fundamentally mode-locked picosecond lasers with up to 77 GHz repetition rate have been demonstrated [9–12]. However, self-referencing of such sources has not yet been demonstrated. In addition, harmonically mode-locked sources can exhibit residual modes at the fundamental cavity frequency [10], posing a limit to the obtainable modulation contrast in optical 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 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 the 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–M3 have a high-reflective negative dispersive coating with approximately $-40\ \mathrm{fs}^2$ group-delay dispersion (GDD) between 750 and 850 nm. Together with the laser crystal contribution, the net cavity GDD is thus approximately $-35\ \mathrm{fs}^2$. The output coupler has 2% transmission. To initiate mode locking, mirror M2 is

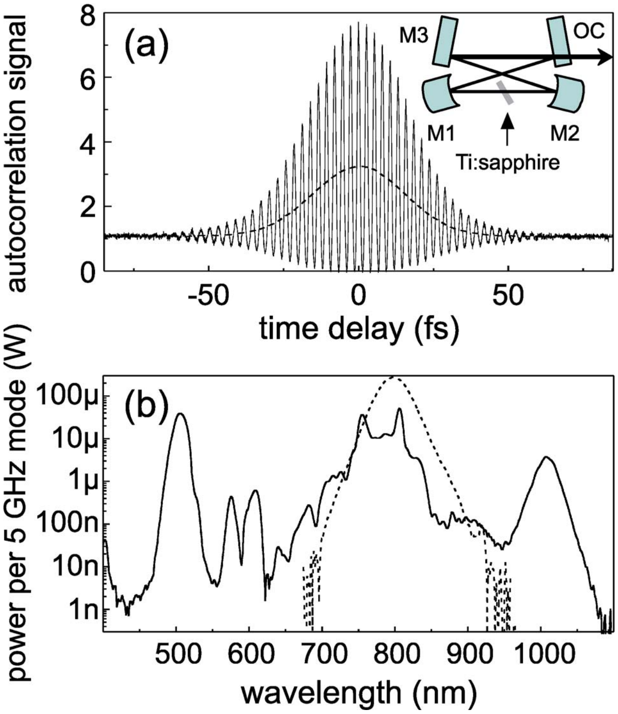

Fig. 1. (Color online) (a) Interferometric autocorrelation trace (solid curve) of the 5 GHz pulses and low-pass filtered trace (dashed curve). Inset: laser cavity schematic. (b) Laser output spectrum in units of power per 5 GHz mode (dashed curved) and octave-spanning spectrum after nonlinear broadening (solid curve).

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. 1(a). 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. 1(b) and has a FWHM of 35 nm centered at ~798 nm. The 5 GHz repetition rate is detected by focusing ~20 mW of optical power onto a high-speed GaAs p-i-n photodiode. The electrical power contained in the 5 GHz signal amounts to −5.7 dBm (into a 50 Ω load) with a direct current of ~5 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 piezocrystal that supports mirror M3.

The carrier-envelope offset frequency f_0 of the laser is measured in an $f-2f$ nonlinear interferometer [15]. Out of the output power 950 mW is launched into a microstructured fiber (1.5 μm core, zero-GDD wavelength at 590 nm) with an efficiency of 35%. The optical output spectrum is shown in Fig. 1(b). A beat signal between the frequency-doubled light at 1000 nm and the fundamental light at 500 nm is detected with an Si p-i-n photodiode [see Fig. 2(a)]. The bandwidth of the photodiode was approximately

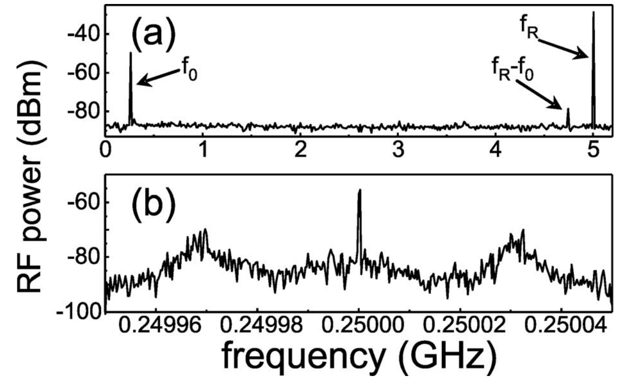

Fig. 2. (a) Self-referencing beat signal of the 5 GHz laser. Resolution bandwidth (RBW) is 300 kHz. (b) Phase-locked f_0 signal with RBW set to 100 Hz.

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. 2(b). 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 diffraction grating (1800 lines/mm) [13,16,17]. The VIPA etalon has a high-reflective coating on the input face (except for an uncoated entrance window) and a 96% reflectance coating for 800 nm on the output face. The spectrally dispersed elements of the FLFC are imaged to a first focal plane where the spatially separated 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. Figures 3(a) and 3(b) show an image covering a portion of the optical spectrum. 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 (~50 GHz). The spacing of the dots is ~90 μm in the vertical direction and ~60 μm in the horizontal direction. These values are

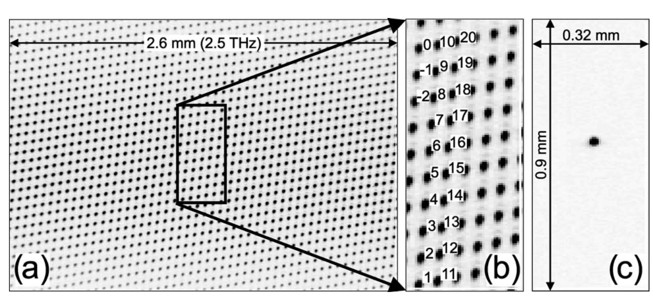

Fig. 3. (a) Output of the VIPA spectrometer recorded with a CCD camera. The image covers ~5 nm centered at ~802.5 nm. (b) Zoom into the CCD image. Successive modes are numbered. (c) Mode 1 isolated with a pinhole.

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 μm diameter pinhole in the first focal plane. Figure 3(c) shows a single isolated mode from the center region of the spectrometer output. A power measurement behind the pinhole shows that the isolated mode contains 2.2 μW of average power.

We have isolated a series of 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). Spectra of the isolated dots numbers 1 and 2 are shown in Fig. 4. Cross talk from modes that are spaced by one or more horizontal spacings (i.e., by multiples of the VIPA FSR) is suppressed by more than 20 dB, implying less than 10% modulation at 50 GHz in the detected power of the isolated mode. Cross talk from modes that are spaced by one or more vertical spacings (i.e., by multiples of f_R) is not resolved by the OSA but is expected to be significantly below 20 dB because the vertical spatial mode spacing is ~1.5 times greater than the horizontal spacing. The center frequencies of the individual modes are extracted from the OSA and plotted versus mode number in Fig. 4. A linear fit to the data yields 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 min). 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.

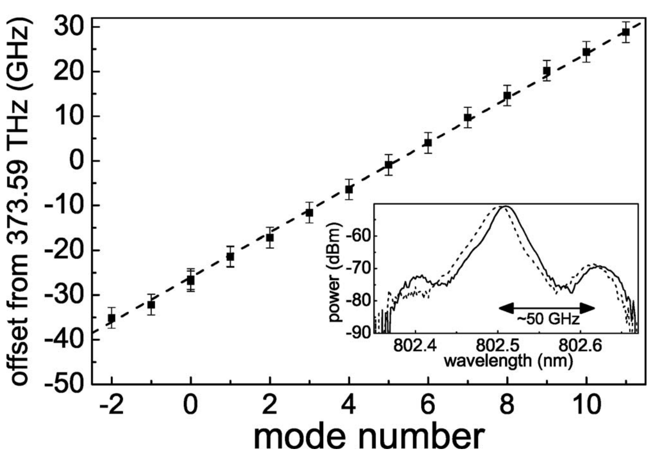

Fig. 4. Mode frequency versus mode number (solid squares) and expected dependence for the 5.000994 GHz repetition rate (dashed line). Error bars represent the frequency repeatability of the OSA. Inset: spectra of modes number 1 (solid curve) and 2 (dashed curve).

A major consideration toward even higher repetition rates is the nonlinear cavity round-trip phase shift Φ_{RT} [18]. Here, we estimate $\Phi_{RT} \approx 200$ mrad, a factor of 4 higher than the lowest value demonstrated for a similar laser [6]. Thus, scaling to at least 10 GHz should be straightforward. We succeeded in shortening the cavity to yield 6 GHz repetition rate with no significant changes to the output characteristics; mechanical constraints prevented higher values. To the best of our knowledge, 6 GHz is the highest repetition rate ever demonstrated for a fundamentally mode-locked femtosecond laser.

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