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Octave-spanning Ti:sapphire laser with a repetition rate >1 GHz for optical frequency measurements and comparisons

T. M. Fortier

Physics Division P-23, MS H803, Los Alamos National Laboratories, Los Alamos, New Mexico 87545

A. Bartels

Gigaoptics GmbH, Blarerstrasse 56, 78462 Konstanz, Germany

S. A. Diddams

National Institute of Standards and Technology, 325 Broadway, MS 847, Boulder, Colorado 80305

We demonstrate a self-referenced, octave-spanning, mode-locked Ti:sapphire laser with a scalable repetition rate (550 MHz–1.35 GHz). We use the frequency comb output of the laser, without additional broadening in optical fiber, for simultaneous measurements against atomic optical standards at 534, 578, 563, and 657 nm and to stabilize the laser offset frequency.

Optical-frequency combs based on mode-locked femtosecond lasers have become the enabling technology for simplified schemes in optical-frequency measurements and comparisons. Beyond the development of optical-frequency standards, these measurements allow for the possibility of laboratory-based searches into the stability of fundamental constants by enabling measurement of the frequency ratios between different and extremely stable atomic clock transitions.[1] The femtosecond laser frequency comb (FLFC) based on the Kerr–Lens mode-locked Ti:sapphire (Ti:S) laser represents the current state of the art in stability and accuracy for such measurements. Recent progress with very broadband Kerr-lens mode-locked Ti:S lasers has increased the usable bandwidth of the optical spectrum[2–6] and simplified the measurements by eliminating the need for additional broadening in optical fibers. To date, however, octave-spanning lasers have been demonstrated with repetition rates up to only 200 MHz. Higher repetition rate lasers that provide more optical power per mode are preferable for optical-frequency metrology. Additionally, octave-spanning lasers provide little light below 600 nm, which makes measurements in this regime difficult. This is a particular issue at NIST, where three of the four current optical-clock standards have local oscillators in this range Al^+ (534 nm), Hg^+ (563 nm), and neutral Yb (578 nm). In this Letter we present techniques for simultaneous measurements at these wavelengths with a variable repetition rate (550 MHz–1.35 GHz) FLFC that has an octave-spanning bandwidth required for f–$2f$ self referencing.[7] We also demonstrate that the FLFC can effectively transfer and reproduce the very low frequency noise of the optical standard to which it is stabilized.

We present a prismless, four-mirror Kerr-lens mode-locked Ti:S ring laser (Fig. 1) that, compared to earlier work,[3] uses commercially available chirped mirrors that exhibit a much broader bandwidth in terms of both reflectivity and group-delay dispersion (GDD) compensation (nominally $-65\ \mathrm{fs}^2$ per bounce over 700–1000 nm). The laser also employs a 1 mm thick fused silica plate at Brewster's angle that provides extra positive intracavity dispersion and that is also used for fine tuning of the laser offset frequency. The laser output coupler has a transmission of 1% and a bandwidth of 200 nm centered at 800 nm. The two curved mirrors, M1 and M2, are a dispersion-compensated pair, each with a radius of curvature of 3 cm. Mirror M3 has a 1 m convex radius of curvature and has the same dielectric coating as M1. Cal-

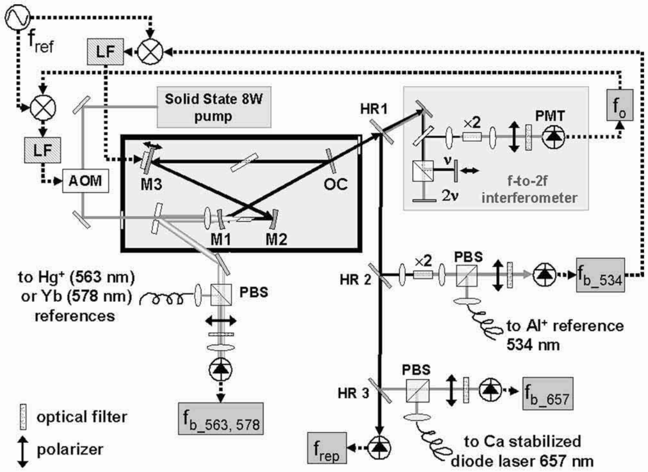

Fig. 1. Schematic of the experimental setup for a compact FLFC. The laser produces pulses that circulate in the cavity in the direction shown. The electronic heterodyne beat signals between the FLFC and the various cw local oscillators are marked as f_{b_i}. HR1, HR2, and HR3 are high reflectors at 580–1100, 1064, and 657 nm, respectively. Narrowband optical filters are used to ensure spectral purity and overlap in each interferometer. In the comparison against 578 and 563 nm light, the combined light after the PBS is coupled into a single mode optical fiber to aid in mode matching. PBS, polarizing beam splitter; AOM, acousto-optic modulator.

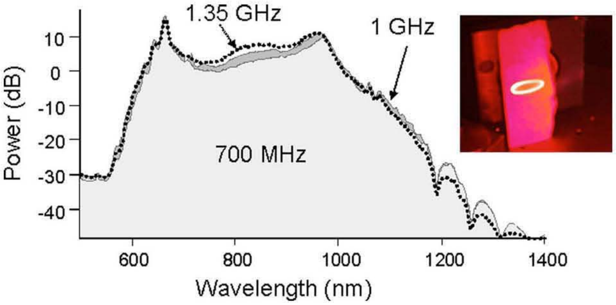

Fig. 2. (Color online) Left, laser output spectrum as a function of repetition rate, f_{rep}. The dark gray shading shows the spectrum at $f_{\mathrm{rep}}=1$ GHz. The dotted curve shows the laser spectrum for $f_{\mathrm{rep}}=1.35$ GHz. Right, mode profile for light in the green portion of the spectrum as taken at the output of M1 (Fig. 1). The spatial profile appears elliptical because the incident beam is at an angle to the camera.

culations indicate that the convex curvature optimizes the spatial mode within the laser crystal such that it enhances the effects of self-amplitude modulation.[8]

With a 2.3 mm Ti:S crystal, we operate the “cold” cavity near zero-average GDD. However, because M3 is unpaired in terms of GDD oscillations, the net dispersion of the cavity yields GDD ripples with a peak-to-peak amplitude of ~100 fs^2 from 700 to 1000 nm. Even with these oscillations in GDD across the center portion of the Ti:S gain bandwidth, we observe a continuum generation in the laser crystal resulting in an “octave-spanning” laser spectrum (see Fig. 2). Such an observation is consistent with self-amplitude modulation being the dominant mode-locking mechanism. This contrasts with lasers from the Kärtner group at MIT, where careful dispersion management over octave bandwidths plays a crucial role in stable broadband operation.[2,5,6]

When pumped with 8.5 W of 532 nm light from a solid-state pump source, the octave-spanning FLFC produces 900 mW of output when mode locked and ~50 mW when running cw. The high average power results because the transmission of the output coupler increases steeply beyond its specified bandwidth (700–900 nm), thus enhancing the spectral wings. We estimate an ~8% loss in intracavity power due to outcoupling of the spectral wings, resulting in a net loss in power of 9% at the output coupler alone, making it possible for the laser to operate in a single-pulsing as opposed to a multipulsing regime. The narrow output coupler bandwidth forces the continuum to be produced in a single pass through the crystal as the pulse traverses from M2 to M1. As seen in Fig. 2, the octave points of the spectrum at 550 and 1100 nm are at a level of −30 and −7 dB, respectively, as compared with light at 800 nm. An interesting characteristic of the generated continuum is that the observed spatial modes are similar to those produced in conical emission (see the inset in Fig. 2), whereby the visible continuum is produced in rings with diameters that increase with optical frequency. Although we are uncertain of the observed modes' physical origin, they may help to reveal the underpinnings of the nonlinear optics behind the creation of such a broadband continuum.

The mode-locked laser spectrum may be likened to an optical frequency comb that is composed of discrete, coherently related, and equally spaced frequency elements. Two frequencies, the laser repetition rate, f_{rep}, and the laser offset frequency, f_o, respectively, determine the comb spacing and the absolute comb position. As a result, each individual element in the comb is described as $\nu_n=nf_{\mathrm{rep}}+f_o$, where n is a large integer (10^5) multiplying the repetition rate (~1 GHz) into the optical. A stabilization of the two characteristic frequencies results in a compact optical frequency reference. However, to easily resolve the absolute frequency of any comb element requires a sufficiently large f_{rep}. The laser presented conveniently has a repetition rate that can be changed from 550 MHz to at least 1.35 GHz (the physical limits of the current cavity). As we increase f_{rep}, there is minimal change in both the output power and the spectrum (see Fig. 2), which is surprising given the strong dependence of broadening on laser-pulse intensity.

To use the laser light most efficiently, the laser output is split by using a mirror that reflects the center portion of the spectrum (580–1060 nm) and transmits only the spectral wings. The spectral wings are used to measure f_o, while the center portion of the spectrum, containing the majority of the laser power, may be used for either optical frequency measurements or time-domain experiments. A compact Michelson interferometer (Fig. 1) enables harmonic comparison between doubled light at 1100 nm versus fundamental light at 550 nm to measure f_o.[7] The fundamental and doubled light are coupled into an optical fiber for spatial mode matching, and the offset frequency is detected with a signal-to-noise ratio (SNR) of 25–31 dB (1.1 GHz–550 MHz) in a 300 kHz bandwidth by use of a photomultiplier tube (PMT). The resulting signal is used in a feedback loop that employs an acousto-optic modulator (AOM) to adjust the laser pump power for stabilization of f_o, resulting in a stabilized in-loop linewidth of f_o that is resolution limited below 1 Hz. The integrated phase noise of the offset frequency was measured to be 0.4 rad in a bandwidth of 500 mHz–102 kHz, and the offset frequency has been observed to stay locked without any appreciable cycle slips for more than 2 days.

As a demonstration of the laser's viability for performing optical frequency measurements and comparisons, we detected the beat signal between the FLFC and the four local oscillators of the existing optical standards at NIST.[9] The oscillators are single-frequency cavity-stabilized dye lasers operating at 534, 578, and 563 nm and a cavity-stabilized diode laser at 657 nm (see Fig. 1). For the cw lasers at 563, 578, and 657 nm we use the fundamental light from the FLFC for the measurements. In the heterodyne against the 534 nm source we use frequency-doubled light at 1068 nm in a 4 mm long $KNbO_3$ crystal (see Fig. 1). In our measurement against the 563 and 578 nm cavity-stabilized dye lasers, we use fundamental light transmitted through cavity mirror M1 for the measurements (see Fig. 1). Because the Ti:S crystal efficiently absorbs green wavelengths and because the cavity mirrors transmit significantly below 600 nm, the spectrum depicted in Fig. 2 represents a small fraction (5% at 532 nm) of the visible light that is produced via the continuum generation in the laser crystal. The majority of the visible light in the yellow–green portion of the spectrum is transmitted through cavity mirror M1 in Fig. 1, back toward the pump source. Because continuum-generated light in the visible is produced in rings, it is efficiently separated from the incoming 532 nm pump beam by using a silver mirror with a hole drilled in it.

By using the light from the octave laser we obtain rf beat signals, $f_{b\_i}=\nu_{\mathrm{opt}\_i}-\nu_n$, between one tooth of the optical-frequency comb, ν_n, and the cw oscillator, ν_{opt_i}. The resulting heterodyne beat signals are detected by using p-i-n photodetectors with SNRs of 40, 33, 25, and 22 dB (in a 300 kHz bandwidth) between the FLFC and light at 657, 534, 578, and 563 nm, respectively. The Ti:S laser comb is stabilized by simultaneously locking the offset frequency and one comb element to any of the previously mentioned cw sources. As a specific example, we lock the FLFC to the 534 nm local oscillator that is referenced to a narrow clock transition in the single Al$^+$ ion standard.[9] The comb is stabilized to the optical reference by using a servo loop that corrects the Ti:S laser cavity length via a mirror that is mounted on a piezoelectric actuator (Fig. 1). By simultaneously stabilizing the laser offset frequency, we transfer the stability of the Al$^+$ standard to each tooth in the optical comb. To verify this transfer, we compare one tooth of the Al$^+$-ion stabilized comb with the cavity-stabilized 657 nm diode laser [see Fig. 3(a)]. Because the 657 nm diode laser is referenced only to a stable cavity, there is a slow drift rate (~5 Hz/s) between the comb and the 657 nm light. As depicted in Fig. 3(b), when we zoom in on the beat signal itself, we recover the expected 3 Hz carrier of the cavity-stabilized cw oscillator. This transfer in stability from the optical standard to the Ti:S laser spectrum demonstrates the octave-spanning combs' viability for performing comparisons between optical frequencies separated by, in this case, 105 THz, with minimal added measurement instability.

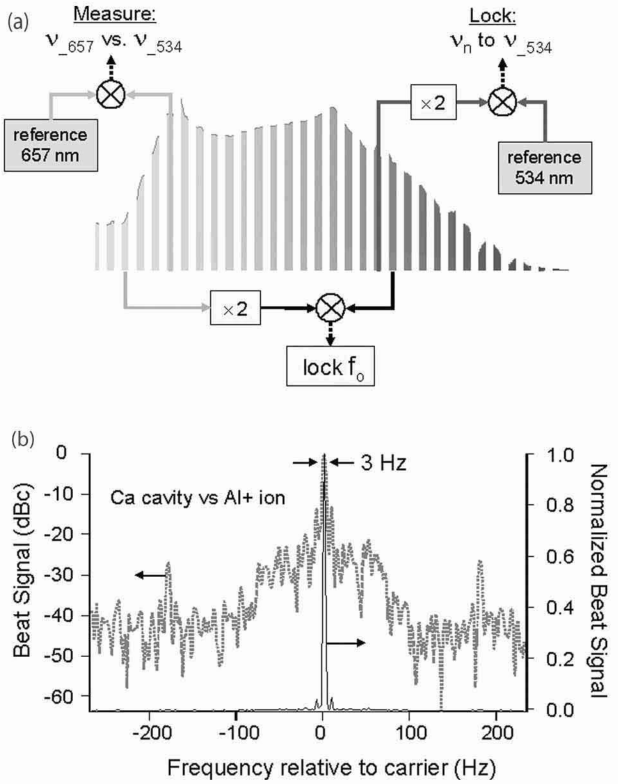

Fig. 3. (a) Depiction of how we verify the stability transfer between the optical standard and the octave-spanning comb. (b) A 3 Hz wide beat signal between the FLFC and a cavity-stabilized diode laser at 657 nm. The signal is shown on a logarithmic (left) and linear scale (right).

In conclusion, we have demonstrated a scalable repetition rate (550 MHz–1.35 GHz) octave-spanning laser with sufficient optical bandwidth to simultaneously measure a direct "*f*-to-2*f*" offset frequency beat signal as well as a beat signal between each of the four local oscillators (534, 563, 578, and 657 nm) for NIST's optical standards. Given the power per mode of the present laser bandwidth, it should be possible to perform optical-frequency measurements and comparisons from 563 to 1200 nm by using fundamental light and from 300 to 550 nm by using frequency-doubled light (600–1100 nm).

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