

Absolute frequency measurement of unstable lasers with optical frequency combs

N. Beverini^a, N. Poli^b, D. Sutyryn^{a,b}, F.-Y. Wang^b, M. Schioppo^b, M. G. Tarallo^b, and G. M. Tino^b

^aDipartimento di Fisica and CNISM, Università di Pisa; Largo Pontecorvo 3, Pisa, Italy

^bDipartimento di Fisica e Astronomia, and LENS, Università di Firenze; Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Polo Scientifico, 50019 Sesto Fiorentino, Italy

ABSTRACT

Here we report on absolute frequency measurements of a commercial high power CW diode-pumped solid-state laser (Coherent Verdi-V5). This kind of lasers usually presents large frequency jitter (up to 50 MHz) both in the short term (1 ms time scale) and in the long term (>10 s time scale). A precise measurement of absolute frequency deviations in both temporal scales should require a set of different devices (optical cavities, optical wave-meters), each suited for measurements only at a specific integration time. Here we demonstrate how a frequency comb can be used to overcome this difficulty, allowing in a single step a full characterization of both short (<1 ms) and long term ($>10^3$ s) absolute frequency jitter with a resolution better than 1 MHz. We demonstrate in this way the flexibility of optical frequency combs for absolute frequency measurements not only of ultra-stable lasers but also of relatively unstable lasers. The absolute frequency calibration of the Verdi laser that we have obtained have been used in order to improve the accuracy of the measurements of the local gravitational acceleration value with ^{88}Sr atoms trapped in 1D vertical lattices.

Key words: femtosecond laser, frequency comb, absolute frequency measurement, Verdi, Dynamical laser instabilities, noisy laser behavior, cold atoms, gravity measurement.

1. INTRODUCTION

Today, optical frequency combs are widely used for many precision measurements, finding their natural application in frequency metrology for the calibration of ultrastable optical frequency referencesⁱ. Other interesting metrological applications of frequency combs has been described in the literature, in which less stringent requirements on frequency stabilization of the comb spectrum is required, as for example in calibrating astronomical spectraⁱⁱ, or in molecular THz spectroscopyⁱⁱⁱ.

In this work, we report the implementation of a Ti:Sa femtosecond frequency comb for the characterization of the frequency stability of a commercial single-mode high power frequency doubled Nd:YVO laser (Verdi-V5 Coherent). This laser has found a wide application as a low noise pump for solid-state Ti:Sa lasers and is often employed in atomic physics experiments as a high power source for dipole trap. This laser is generally characterized by a low AM noise, but it can show a quite large frequency jitter (>50 MHz) both in short term (<1 ms) and in long term (>10 s).

Here we demonstrate how an optical frequency comb can be used to measure the absolute frequency jitter at different temporal scales, showing how these device can find application also to perform precise absolute frequency characterization of unstable lasers. These measurements are of particular interest in the field of atomic physics in which high power CW solid state laser are typically employed to trap cold atoms in far off-resonance optical dipole traps with different geometries, ranging from single beam trap, crossed beam traps or multidimensional optical lattices. Especially in the last case, information about frequency jitter is important, since in this kind of trap laser frequency noise may convert in position fluctuations of the trap wells, resulting in additional atom losses.

Here the absolute calibration of Verdi laser emission frequency have been used to improve the accuracy of the measurements of the local gravitational acceleration value by the use of ^{88}Sr ultra-cold atoms trapped in 1D vertical realized with radiation from Verdi laser.

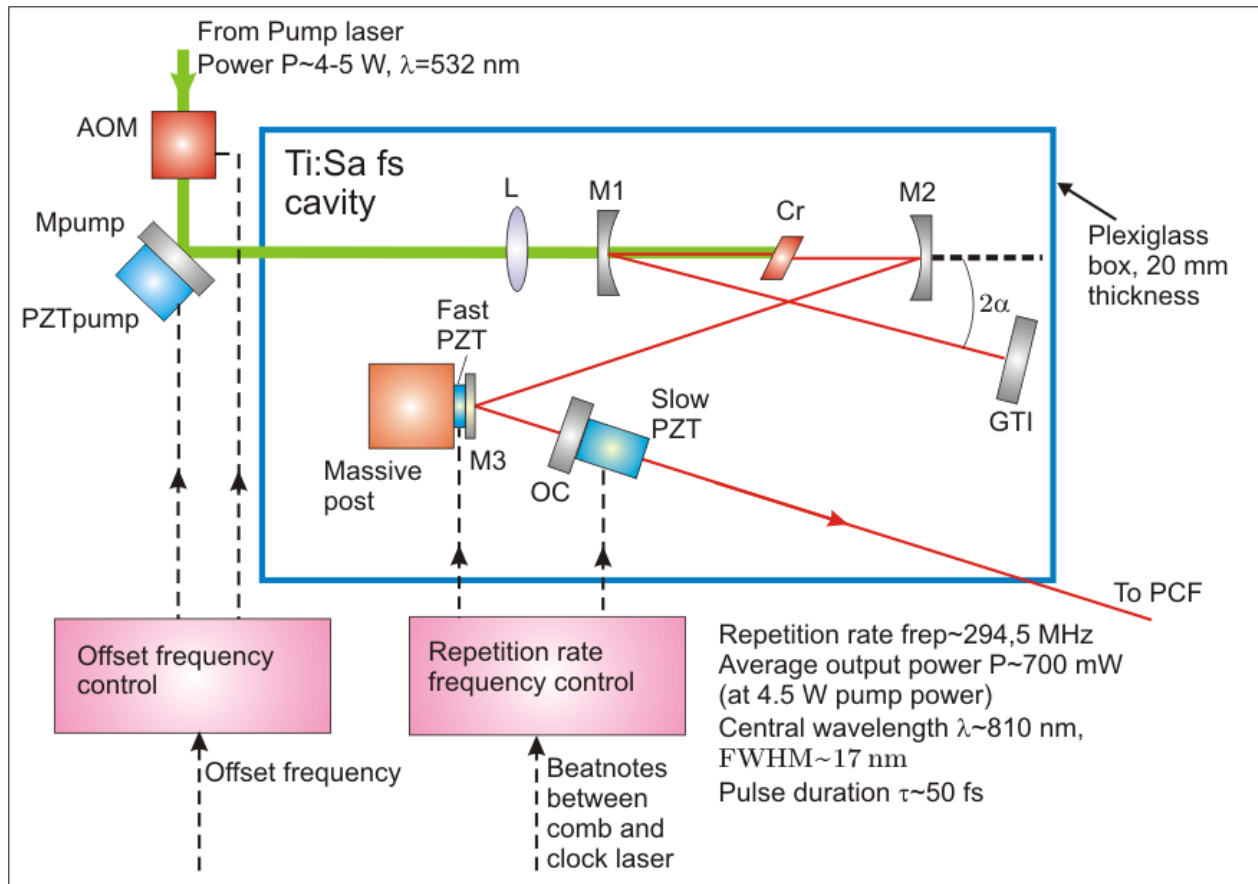


Figure 2: Experimental setup of Ti:Sa optical frequency comb cavity. L - lens, M1 and M2- curved mirrors, M3 - flat mirror, OC - output coupler, GTI - Gires-Tournois interferometer mirror, α - astigmatism compensation angle, PCF - photonic crystal fiber.

mode laser (Coherent Verdi-V5[®]).

Fig.2 shows the design of the femtosecond laser with a detailed scheme of the Ti:Sa cavity. The fs laser cavity is composed by two curved mirrors (M1 and M2), one 2.5 mm-long Ti:sapphire crystal (doped at 0.25%) one high reflective Gires-Tournois interferometer type flat mirror (GTI) with dispersion -550 fs², which is used to compensate the intracavity dispersion, and one output coupler (OC) with 3% transmission coefficient at 800 nm. An additional 1/4" inch diameter flat folding mirror (M3) with zero dispersion has been inserted in the cavity to allow fast (up to 40 kHz) control of the cavity length through a PZT. The overall estimated intracavity dispersion is about -200 fs², while the total length of the cavity is ~ 510 cm.

All the mirrors (except the output coupler) are dielectric with $>99\%$ reflection coefficient at the center wavelength of 800 nm. The curved mirrors (radius of curvatures 25 cm) are both aligned to form X-shape cavity with an incidence angle $\alpha = 8^\circ$ that compensates the crystal astigmatism. The pump beam is coupled into the cavity through the curved mirror M1 and is focused on the crystal through a lens with focal length 7.5 cm. The flat side of the input mirror M1 is AR coated at 532 nm to minimize losses. A second piezoelectric transducer on the OC mirror of the Ti:Sa cavity allows the slow control of the cavity length.

The emission spectrum of the Ti:Sa mode-locked laser is centered around 810 nm with a typical FWHM of about 17 nm. The laser output is then coupled into a photonic crystal fiber (Femtowhite 800[®]) that broadens the spectrum up to a full optical octave (from 400 nm up to 1100 nm). The maximum power obtained at the fiber output is 350 mW, but in order to reduce the wideband frequency noise generated in the fiber at high intensity, we usually work with less than 250 mW.

The carrier envelope offset (CEO) frequency f_{CEO} is measured with a standard $f-2f$ interferometer^{ix} with a non-linear 3mm-long BBO crystal (in type I configuration) placed in the first interferometer arm. The slow drift of offset frequency is corrected by actuating through a PZT on the position of the pump mirror (PM), while the fast fluctuations (up to 100 kHz) are corrected by acting on pump power through the use of an acusto-optical modulator (AOM).

The common way to stabilize the comb repetition rate is either to lock it to an RF standard or, to increase its stability, to lock the beatnote between one tooth of the frequency comb and an optical standard. This is done typically by using PLL servo electronics acting on cavity PZTs. Note that, in the case of direct stabilization in the optical domain, the frequency stability of the optical standard will transfer to all comb components, and the frequency noise on the repetition rate signal is reduced by a factor n :

$$f_{rep} = (f_V \pm f_{CEO} \pm f_b) / n,$$

where f_V is the Verdi frequency, f_{CEO} is the CEO frequency, f_b is the beat-note between a comb tooth and the optical standard and n is an integer defining the comb tooth that has a value of the order of 10^6 .

3. EXPERIMENTAL RESULTS

In our case, we want to measure a laser frequency characterized by a quite large jitter. The output radiation from the 200-m fiber transfer is superimposed in a polarization beam-splitter with the radiation from the femtosecond comb (filtered at $\lambda = 532 \pm 5$ nm). The beat signal between the Verdi laser and the nearby tooth of the comb is detected on a fast photodetector and observed on a rf spectrum analyzer. A typical registration is presented in Fig.3a, which evidences that in a time scale of a few ms, the linewidth is about 10 - 15 MHz broad, due to Verdi laser fast frequency jitter^x. Due to the typical low signal to noise observed (< 25 dBm on a 300 kHz bandwidth) and the fast frequency jitter, it is not possible to use standard frequency counters to perform precise frequency measurements.

We overcome this difficulty by locking the repetition rate of the comb to this *unstable* reference, stabilizing the beatnote frequency.

For this purpose, after the detection on the photodiode, the beat note signal is amplified, filtered and split in two channels. One channel is used to monitor the comb stabilization, while the second one is sent to a phase-frequency detector (PFD). The reference signal for the stabilization (sent to the second PFD input) is given by a local 30 MHz generator, referenced at long term to GPS reference signal. The servo signal for stabilization generated by the PFD (that is proportional to phase difference between the two input signals) is then sent to a PID (proportional-integrated-derivative) controller that is used to actuate two PZT attached to two comb cavity mirrors for slow and fast (up to 40 kHz) cavity length change.

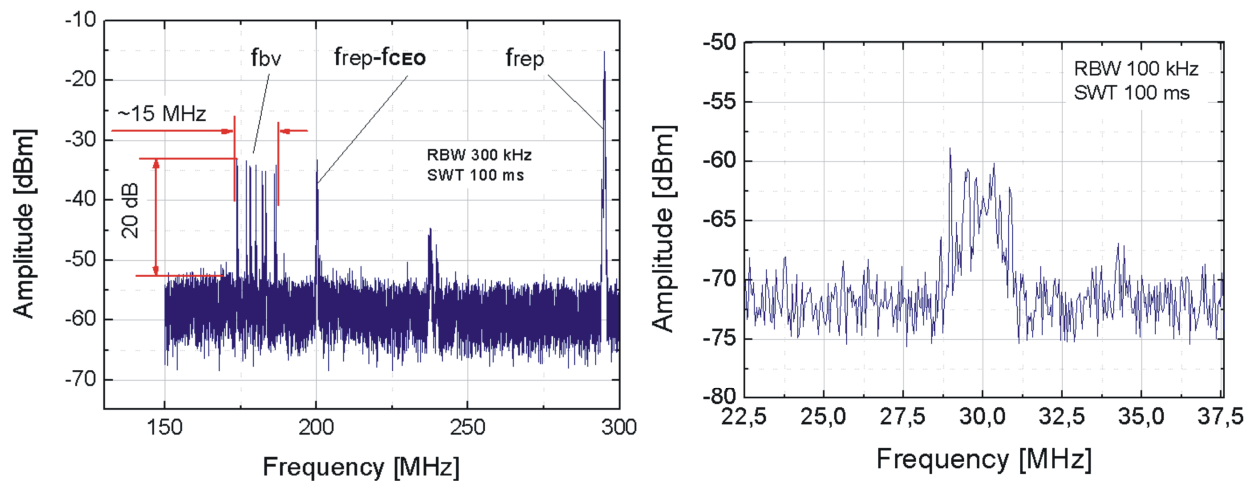


Figure 3: Beat-notes between Verdi and the optical comb, a) left, free-running regime, b) right, with the comb repetition rate locked on the beat-note signal.

After detection the beat note signal is amplified, filtered and split in two channels. One channel from RF power splitter is used to monitor the comb stabilization, while the second one is sent to a phase-frequency detector (PFD). The reference signal for the stabilization (sent to the second PFD input) comes from a local 30 MHz generator, referenced at long term to GPS reference signal. The servo signal for stabilization generated by the PFD (that is proportional to phase difference between the two input signals) is then sent to a PID (proportional-integrated-derivative) controller that is used to actuate two PZT attached to two comb cavity mirrors for slow and fast (up to 40 kHz) cavity length change.

In lock condition, as shown in (Fig. 3), the beat-note signal is stabilized at 30 MHz and the frequency jitter is then imposed on frequency comb repetition rate. Thanks to the large de-multiplication factor of the comb ($\sim 1.9 \times 10^6$) the 10 - 15 MHz frequency jitter at 532 nm gets divided down to about 1 Hz and imposed on the repetition rate signal that is typically observed with $S/N > 50$ dB over a bandwidth of 300 kHz. The repetition rate signal is then easily counted with a frequency counter set with 1 s gate time.

In order to determine the absolute frequency of the Verdi we also count the CEO frequency. In our setup this signal is sufficiently long term stable compared to Verdi frequency instabilities, so that a stabilization of this signal was not required for this measurement. In this case, the absolute value of the Verdi frequency is given by equation $f = n \cdot f_{rep} \pm f_{CEO} \pm f_b$. To determine the correct tooth number at the beginning and at the end of each measurement we employ a lambda meter, calibrated with a stabilized laser resonant with the 689 nm $^1S_0 - ^3P_1$ ^{88}Sr transition, that allows an evaluation of the Verdi laser frequency with an uncertainty of the order of 100 MHz.

In Fig. 4 the result of an absolute frequency measurement that lasts for about 10^4 s is shown. Long term deviation of Verdi frequency greatly depends on many factors, mainly related to temperature, and laser power setting. To increase long term stability we performed this measurement after that the laser was operating continuously for a long time (about two days) at the same power setting. Moreover, we covered the laser head with thermal insulation foam to increase the passive temperature stability

From this measurement we can clearly see periodical deviation of the frequency at two different regimes. Firsts, we observe a long-term oscillation of the Verdi frequency with period ~ 1000 s and amplitude 130-140 MHz. Secondly, there is a fast oscillation with a shorter period ~ 33 s and an amplitude 30 - 70 MHz with typical value 30 - 50 MHz (see Fig. 4 inset). The missing data in this set are caused to a comb unlocking from the Verdi signal.

We think that this represents a lower limit for long-term frequency fluctuations of non-stabilized Verdi laser for the reasons explained above. After shutdown period, these lasers can show in fact both quite different absolute frequency (offset by several GHz) and large frequency drift rate at start up (up to 100 MHz in one minute).

As shown in the inset of Fig. 4, absolute determinations of the instantaneous value of the Verdi frequency (in the case of the measurement shown in Fig. 4 the mean value is $563\,257\,825 \pm 75$ MHz) can be in this way performed with a sub-MHz resolution. This value can eventually be used to determine gravity with 10^{-7} relative uncertainty, by observing at the same time Bloch oscillation of ultra-cold ^{88}Sr atoms trapped in vertical standing wave.

4. CONCLUSION

We made the absolute frequency measurement of the Verdi-V5 with sub-MHz resolution and observed the fast and the slow behavior of its frequency by the use of a femtosecond frequency comb. The frequency measurement have been used in accurate determination of gravity by the use of ^{88}Sr atoms trapped in vertical lattices. This work demonstrates the great flexibility of optical frequency combs for precision measurements of optical frequencies of unstable lasers. This study in turn may also be important for the study of stabilization technique of CW solid-state diode pumped lasers and moreover could be important for the study of Ti:Sa femtosecond lasers dynamics.

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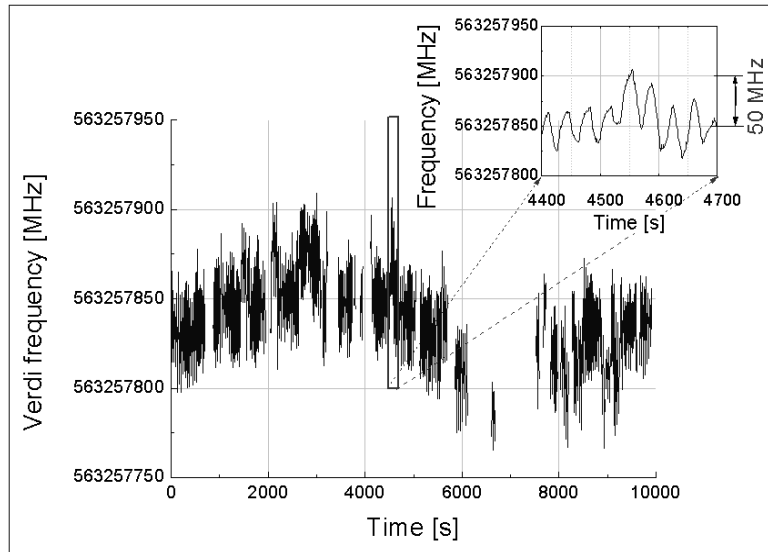


Figure 4: Verdi Absolute frequency measurement. In the inset are shown the Verdi frequency fluctuations at shorter time scale.

REFERENCES

- [i] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical Frequency Metrology", *Nature* 416, 233-237 (2002)
- [ii] T. Steinmetz et al., *Laser Frequency Combs for Astronomical Observations*, *Science* 321, 1335-1337 (2008)
- [iii] N. Beverini, G. Carelli, A. De Michele, E. Maccioni, B. Nyushkov, F. Sorrentino, A. Moretti: Coherent multiwave heterodyne frequency measurement of a FIR laser by means of a femtosecond laser comb, *Opt. Lett.* **30**, 32-34 (2005)
- [iv] N. Poli, M. G. Tarallo, M. Schioppo, C. W. Oates, S. Chepurov, D. Sutyryn, A. De Michele, N. Beverini and G. M. Tino, "Strontium Optical Lattice clock" *Proc. of the 5th International Symposium "Modern Problems of Laser Physics" (MPLP'2008) Novosibirsk, Russia, August 2008*, pp. 327-334 (2008).
- [v] N. Poli, M. G. Tarallo, M. Schioppo, C. W. Oates and G. M. Tino, "A simplified optical lattice clock", *Appl. Phys. B* 97, 27-33 (2009)
- [vi] N. Poli, G. Ferrari, M. Prevedelli, F. Sorrentino, R. E. Drullinger, G. M. Tino, "Laser sources for precision spectroscopy on atomic strontium", *Spectrochimica Acta A* 63, 981-986 (2006)
- [vii] F. Sorrentino, G. Ferrari, N. Poli, R. E. Drullinger, G. M. Tino, "Laser cooling and trapping of atomic strontium for ultracold atoms physics, high-precision spectroscopy and quantum sensors", *Mod. Phys. Lett. B* 21, 1287-1320 (2006)
- [viii] G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, "Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale", *Phys. Rev. Lett.*, 97, 60402 (2006)
- [ix] H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation", *Appl. Phys. B* 69, 327 (1999)
- [x] Coherent report: "Wavelength Control White Paper". Web link: www.coherent.com/Lasers/index.cfm?fuseaction=show.page&id=1852