ABSOLUTE FREQUENCY MEASUREMENT OF AN I_2 STABILIZED Nd: YAG OPTICAL FREQUENCY STANDARD

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We report the first results obtained with a new frequency measurement chain based on a femtosecond laser. The frequency of an I_2 stabilized Nd:YAG optical frequency standard, developed at the BNM-INM as a national standard for the "mise en pratique" of the definition of the meter, has been measured for the first time.

1 Introduction

Until recently the absolute measurement of the frequency of an optical frequency standard (OFS) was only possible with a very complex setup that links phase-coherently the optical domain to the microwave definition of the time/frequency unit. Such setups, which we will call classical harmonic chains, were based on frequency multiplication in nonlinear elements, allowing only low multiplication order. A large number of intermediate oscillators was therefore necessary.

This picture is dramatically changing owing to the fortunate coincidence of two independent developments. The first is the development of Kerr-lens mode-locked femtosecond lasers. The soliton-like property of the short pulses propagating within the laser cavity provides in the frequency domain an extended grid of discrete phase-coherent lines equally spaced by the repetition rate Δ of the pulse train [1, 2]. When Δ is phase-locked to a microwave clock, the spectral output of such lasers can be used as an accurate frequency difference ruler. The second event is the development of the photonic bandgap crystal fibre (PCF), carried out at the university of Bath [3] and in Lucent research labs [4]. This fibre permits one to broaden the frequency comb of the femtosecond laser over more than one octave, spanning from less than 500 nm to more than 1100 nm, in the case of Ti:Sa lasers.

Thanks to these recent developments, the direct link between the cesium primary microwave frequency standard and visible or near infrared frequency standards is considerably simplified, as compared to the recent past. In the simplest implementation of the octave-spanning setup as a frequency chain, the measurement of an unknown frequency f is made possible by measuring the difference $2f - f = f$ between f and its second-harmonic $2f$, provided that both fall within the comb span. The resulting difference $f = N\Delta \pm b_i \pm b_v$ depends only on the repetition rate value, on the fractional beat frequencies $b_{i,v}$ of f and $2f$ respective to the adjacent fs laser modes, and on the number N of inter-mode spacings. The particular case of the measurement of an I_2 stabilized Nd:YAG frequency standard utilizes this simple implementation.

The development of a measurement chain based on a femtosecond laser has started recently in our laboratory [5], with the aim of measuring the frequency of frequency standard based on cold strontium atoms, which is currently being developed [6]. As first step we have begun by setting up the system for the measurement of the Nd:YAG optical frequency standard, that is the simplest configuration.

2 Experimental setup

A simplified diagram of the setup used for the measurement of the I_2 stabilized Nd:YAG laser is reported in Fig. 1. A prism-less Kerr lens mode-locked Ti:Sa laser (Gigaoptics), with a repetition rate of about 840 MHz, is used to produce a frequency comb centered at about 800 nm and extending over more than 40 nm. The output power of this laser is about 500 mW for 5 W of pumping power.

The spacing of the lines of the frequency comb is imposed by phase locking the repetition rate of the fs laser to the signal from an Hydrogen maser [1]. The frequency of the maser is known by direct comparison with a primary atomic frequency standard. To obtain good phase noise performances, the 11^{th} harmonic of the repetition rate is mixed with the signal from a microwave synthesizer driven by maser signal.

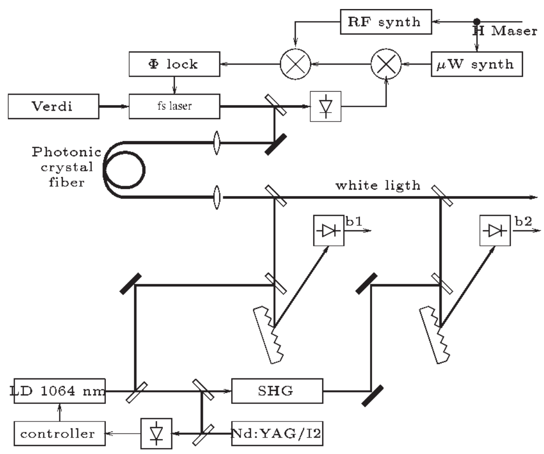

Figure 1: Simplified schematic of the measurement setup

The resulting beat-note is phase compared with the signal from a low noise commercial radio frequency synthesizer to generate the error signal. The phase lock loop is closed by a classical PI controller that steers the position of the flat chirped mirror of the laser's cavity via a piezodriver.

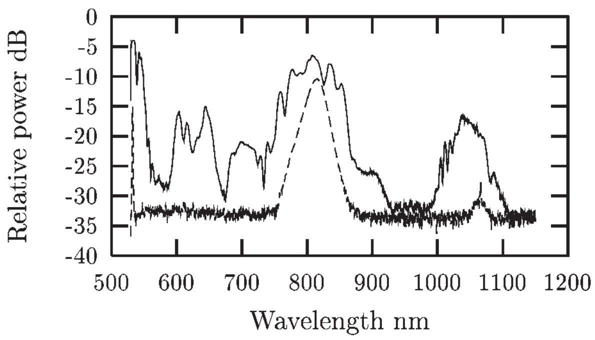

Figure 2: Typical spectrum of the light emerging from the photonic crystal fibre. The dashed line represents the spectrum of the signal entering in the fibre. The reference level is arbitrarily chosen for display purposes.

Once broadened by a photonic crystal fibre (PCF) [3] the frequency comb spans over more than one octave, as sowhed in Fig. 2. The spectrometer used to record this spectrum only operates at wavelength longer than 530 nm, but the actual spectrum covers much of the blue region as well. The wavelengths of the peaks and troughs in the spectrum can be adjusted by rotating the polarization at the input of the fibre by using a zero-order $\lambda/2$ waveplate.

In order to get more power at 1064 nm and to remove the modulation of the signal coming out from the Nd:YAG optical frequency standard, we use the experimental setup described in [7]. It comprises a tunable αDFB (angled-grating distributed-feedback) laser diode operating at 1064 nm that is phase locked to the Nd:YAG signal with an offset of 640 MHz. The phase lock allows to compensate the modulation of the standard by substracting to the error signal a voltage proportional to the modulation. A KTP crystal is used to frequency double the output radiation of the laser diode.

The low frequency part of the white light beam emerging from the micro-structured fibre, is picked-up with a 1064 nm dielectric mirror, that introduces a negligible attenuation on the visible part of the comb. Owing to the chromatic aberration of the objective used at the output of the fibre, this beam is divergent and therefore is collimated by a telescope (not shown in Fig. 1). A plate beam-splitter is used to superimpose this signal to the radiation from the 1064 nm laser diode. To avoid excess shot noise on the photodiode detecting the beat-note, we use a 1200 grooves/mm diffractive grating that spatially disperses the comb spectrum. In this way, only the lines with a frequency in the neighbourhood of the frequency of the CW beam impinge on the fast InGaAs photodiode. The detected beat-note usually exhibits a signal to noise ratio exceeding 30 dB in a 100 kHz bandwidth.

A similar setup is used to obtain a beat-note between the upper part of the comb and the green radiation, giving a similar signal to noise ratio on a silicon avalanche photodiode. At the output of the photodiodes several beat signals are available, at least the beats between the CW laser signals and the adjacent lines of the comb, and the beat between consecutive modes of the comb, that corresponds to the repetition frequency. Among all these signals, we choose at the output of the infrared photodiode the signal corresponding to b_i of Fig. 3, by means of a tunable filter. In the same way we take at the output of the visible photodiode the signal corresponding to b_v.

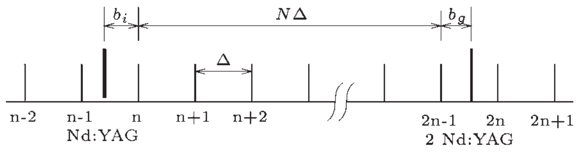

Figure 3: Representation of the beat-notes used in the measurement

These signals can be easily identified by moving the frequency of the comb or of the Nd:YAG laser. From Fig. 3 it is evident that the sum of $b_i + b_v$ is independent from the fluctuation of the offset frequency of the comb. In this case the measured frequency span is $f = b_i + b_v + N\Delta$. To avoid problems related to synchronous counting [8] the sum of the beat notes b_i and b_v is performed analogically with a double balanced mixer. A tracking oscillator is used to clean up the signal before sending it to a frequency counter.

3 Experimental results

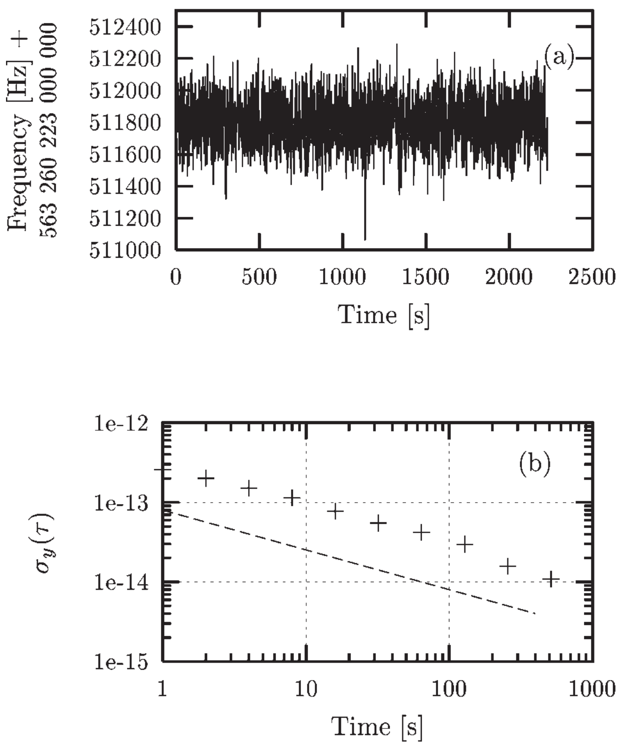

Figure 4: Frequency of the Nd:YAG optical frequency standard (a) and relative Allan standard deviation $\sigma_y(\tau)$ (b)

As an example of the results obtained we report in Fig. 4 the recorded frequency of the Nd:YAG optical frequency standard and the Allan standard deviation calculated from the same dataset. To test the probability of occurrence of cycle slips in the tracking oscillator we have used two of such devices, operating with different control bandwidth. The absence of cycle slips was verified by measuring the frequency of the two output signals with synchronized counters, and carefully checking that the difference on readings was only due to the 1 Hz counter's resolution. The results obtained in three measurement sessions

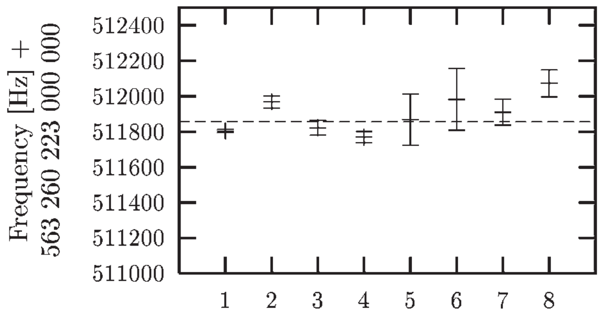

Figure 5: Frequency of the Nd:YAG frequency standard

distributed over more than 1 month are reported in Fig. 5. Each point of this figure is obtained by averaging the series of quasi-consecutive frequency samples obtained with a gate time of 1 or 10 s, eventually removing a few outliers that are clearly identifiable as a consequence of technical noise.

To average the measured values of Fig. 5 it must be considered that each point is issued from a run of different duration and different noise properties. Therefore we need some estimate of the confidence of each measurement in order to have a weighting coefficient. If we consider the frequency standard affected by white frequency noise the classical variance is not the good estimator of the uncertainty because it does not decrease when the average time increases, and worse it can increase in the case we have reached the flicker floor. On other hand the classical variance divided by the square root of the number of samples, is too optimistic in the case of flicker frequency noise. To give a reasonable weight to each frequency measurement we have taken as statistical uncertainty the lowest point that can be identified in the Allan standard deviation. We have not able to found in literature explicit reference to this procedure but we think that is the good compromise when independent samples that are obtained as result of time series of different length must be considered. The error bars in Fig. 5 represent this type of uncertainty used as weighting factor in combining the ensemble of samples.

By averaging results obtained in three different sessions distributed over more than 1 month we obtain for the frequency of the BNM-INM Nd:YAG optical frequency standard:

$$\nu_{green} = 563\ 260\ 223\ 511\ 857\ (88)\text{Hz} \qquad (1)$$

The given uncertainty only takes in account the statistical dispersion of the data collected in this measurement campaign, without accounting for the reproducibility of the standard after transportation or complete realignment. To completely characterize the long term reproducibility successive measuring campaign has to be accounted for. No attempt was made to evaluate systematic frequency shifts of the frequency of the standard. We assume 1 kHz as reproducibility of the frequency of the OFS, this value was found during an international comparison held at the BIPM [9]. The reproducibility was not intentionally tested during this campaign, i.e. only daily readjustment of mains parameter was performed. The standard was never moved neither heavily misaligned to test the overall reproducibility.

The reported frequency value is in reasonable agreement with the recent publication in the domain. Actually the result of our measurement differs only by a few kHz from the results obtained at JILA [10] and at the Max Plank Institute [11], and this difference agrees with other comparison of similar standards with different Iodine cells [12].

From the results obtained in this work it is evident that the frequency chain can be used to compare frequency standards in the microwave and optical domains at a level of $2.5 \cdot 10^{-13}$ at 1 s integration time and at $1 \cdot 10^{-14}$ for a 1000 s averaging.

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