Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

# Optical Frequency Measurements at BNM-SYRTE

G. D. Rovera †, J.-J. Zondy †, A. Brusch †, D. Kolker †, J.-P. Wallerand ‡,
J. C. Knight §, P. St. J. Russell §, W. J. Wadsworth §
† BNM-SYRTE, UMR 8630 Observatoire de Paris, 61 av de l'Observatoire 75014 Paris France
‡ BNM-INM/CNAM, 292 rue St. Martin 75003 Paris, France
§ Optoelectronic Group, School of Physics University of Bath, Bath BA2 7AY UK
e-mail: daniele.rovera@obspm.fr

We report recent results obtained with the frequency measurement comb at the BNM-SYRTE in Paris. Several absolute frequency measurement have been performed: the frequency of some optical frequency standards, as well optical transitions of the strontium atom, relevant for the development of a new optical frequency standard.

## I. Introduction

In the last years the development of Kerr-lens mode-locked lasers, and Photonic Crystal Fibers (PCF) [1], [2], have given a remarkable improvement in phase coherent frequency transfer from the microwave frequency domain of the cesium primary standard to visible and near infrared frequencies.

In the Paris Observatory, the frequency comb replaces the traditional harmonic chain in its role of measuring national references. It is also aimed to become the "gear-box"for the frequency standard based on cold strontium atoms, currently being developed in our laboratory.

Two different OFS developed at the BNM-INM for a national standard for the "mise en pratique" of the definition of the meter have been measured with our current setup. In this paper we will present measurements of an $I_2$-stabilized Nd:YAG laser at 532 nm and an $I_2$-stabilized HeNe laser at 633 nm.

In the early stage of the realization of the new optical frequency standard based on laser-cooled strontium the first milestone is the determination of the frequency of the forbidden transition connecting the ground state to the $^3P_0$ level. This has been achieved by a frequency measurement campaign of several lines afferent to the $^3P$ triplet.

## II. Experimental setup

A simplified diagram of the setup used for the measurement of different OFS is shown in Fig 1. A Kerr lens mode-locked Ti:Sa laser (Gigaoptics) with a repetition rate of approximately 840 MHz produces a frequency comb extending over more than 40 nm. The output power is about 550 mW for 5.5 W pumping power. The spacing of the comb lines is controlled by phase locking the repetition rate of the laser to a hydrogen maser, referenced to a primary frequency standard. To obtain good phase noise performance the $11^{th}$ harmonic of the repetition rate is mixed with the signal from a microwave frequency synthesizer operating at 9.19 GHz. The resulting beatnote is phase compared to a low noise commercial frequency synthesizer to generate the error signal. The phase lock loop is closed by a PI controller that steers the position of one of the cavity mirrors.

The output pulses from the fs laser are spectrally broadened by coupling them into in a PCF to cover more than one optical octave, as shown in fig.2. The shape of the spectrum can be adjusted by rotating the polarization and the coupling at the input of the fiber.

The light from the fiber is separated into different spectral components. The low frequency part of the light around 1064 nm is picked out by a dichroic mirror and frequency doubled in a KTP crystal. The doubled light is superimposed to the green part of the comb and the resulting beam impinges on an avalanche photodiode. The detected beatnote is the carrier envelope offset frequency $\nu_{OFF}$. In a typical measurement, this beatnote exhibits a 40 dB signal-to-noise ratio in a 100 kHz bandwidth.

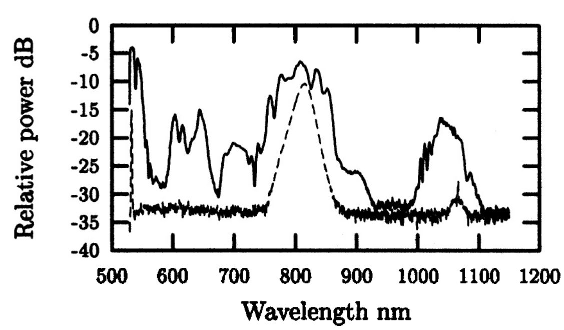


Fig. 2. Typical spectrum of the light emerging from the photonic crystal fiber. The dashed line represents the spectrum of the signal entering in the fiber. The reference level is arbitrarily chosen for display purposes. (The span is limited by the spectrometer, but the comb also cover the blue region)

To perform measurements of different OFS, light at the relevant frequencies in the spectrum is taken out with

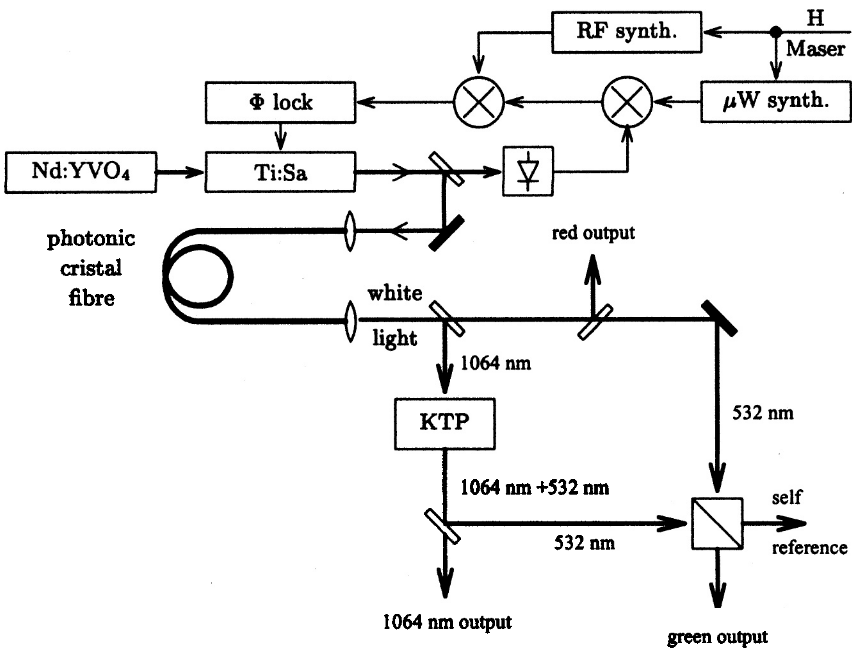


Fig. 1. Schematic of the measurement setup with the outputs for measurement of different OFS

dichroic mirrors located at different points in the setup shown in fig. 1.

To detect the beatnote between a given OFS and the adjacent line of the enlarged comb, the two beams are spatially overlapped in a polarizing cube beam splitter. A $\lambda/2$ wave-plate and a second polarizing cube are used to project the non interfering orthogonal polarizations in a chosen plane, allowing a continuously adjustable ratio. To improve mode-matching the two beams are coupled into a single mode polarization maintaining fiber.

This setup greatly simplifies the alignment, especially when detecting weak beatnotes, because it guarantees the perfect spatial overlap of the light coming from the single mode fiber. In fact all the radiation that reaches the photodiode contributes to the beat signal, then the two beams can be aligned independently for the maximum DC output of the photodiode.

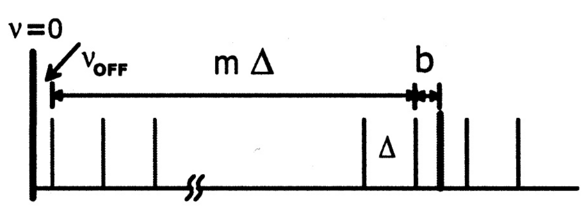


Fig. 3. Representation of the beatnotes used in the experiment

The frequency is found by adding the offset frequency $\nu_{OFF}$ and the beatnote $b$ between the OFS and the adjacent tooth of the comb, as shown in fig. 3. To prevent problems with synchronous counting, the sum is done analogically with a double balanced mixer. The sum beatnote is cleaned up with a tracking oscillator before being sent to a frequency counter. In order to determine the frequency $\nu = \nu_{OFF} + b + m\Delta$ of the OFS one also needs to determine the number of mode spacings ($m$), which is done with a commercial wavemeter or by.

## III. Experimental results

### A. Nd:YAG/$I_2$

The measurement of the $I_2$-stabilized Nd:YAG has been performed on the green second harmonic of the Nd:YAG laser using the above described setup, except for the first measurement campaign where a different setup, described in [3], has been used. The beatnote with the frequency comb yielded a 40 dB signal-to-noise ratio in a 100 kHz bandwidth. The frequency has been measured in several sessions between realignments, and the best results give a relative Allan standard deviation $\sigma_y(\tau)$ of $2{\cdot}10^{-13}$ at 1 s. The short time stability is limited by the noise of the comb frequency chain, and goes down with a $\tau^{-1/2}$ slope due to the counting process that introduces a dead time between measurements. Work is in progress to reduce the noise of the comb and we expect to reach the ultimate stability of the $I_2$-stabilized Nd:YAG OFS.

Recently the Nd:YAG/$I_2$ OFS has been modified to a more compact setup and the characterization is not yet finished, therefore we report only the result obtained in the previous campaign.

$$\nu_{green} = 563\,260\,223\,512\,179\,(260)\ \text{Hz} \qquad (1)$$

No correction is applied in order to give the frequency of the unperturbed iodine transition. The given uncertainty is the standard deviation of the collected data.

### *B. HeNe/$I_2$*

Measurement of the $I_2$-stabilized HeNe required an intermediate laser due to the low output power (approx. 50 $\mu$W) of the laser. For this a second free running HeNe laser has been used, and the beatnote between the two lasers has been detected with an avalanche photodiode, giving a signal-to-noise exceeding 40 dB in a 100 kHz bandwidth. This beatnote then has been mixed with the beatnote between the free running HeNe laser and the frequency comb to cancel out the frequency drift of the free running HeNe laser and obtain a signal equivalent to the beat frequency between the $I_2$-stabilized HeNe and the comb, allowing the same measurement scheme as for the $I_2$-stabilized Nd:YAG.

We have measured a relative Allan standard deviation of $5 \cdot 10^{-12}$ at 1 s dominated by the intrinsic withe frequency noise of the $I_2$-stabilized HeNe. By averaging all significant measurement we have obtained for the f component of the R11-5 line of 127 $I_2$:

$$\nu_{633} = 473\,612\,353\,568\,520\,(320)\ \text{Hz} \qquad (2)$$

The given (in)stability is the standard deviation of the data collected, and must not be interpreted as the accuracy. This measurement differs of about 29 kHz from the recommended value, and need to be reconfirmed. In fact when the HeNe/$I_2$ OFS has been returned to the BNM-INM whey have found a frequency shift of several kHz, due to a bad thermal contact in the cell temperature controller.

### *C. Strontium*

The comb has been used in a measurement campaign aimed to the precise determination of several optical transitions afferent to the 3P triplet of the Sr atom. The role of the comb laser in this task has been the quasi continuous measurement of the frequency of the ultra-stable laser used as local oscillator in the Strontium laboratory.

At the output of the 35 m long polarization maintaining optical fiber, that links the Strontium laboratory to the femto optical table, about 200 $\mu$W of red light are available. This power allows a beatnote of about 20 dB signal-to-noise ratio in a 100 kHz bandwidth. Once summed to the comb offset $\nu_{OFF}$ this signal is sufficient to drive a tracking oscillator without detecting any cycle slips. The measurement of the cavity frequency can reach a relative Allan standard deviation $\sigma_y(\tau)$ of $2 \cdot 10^{-13}$ at 1 s. At longer

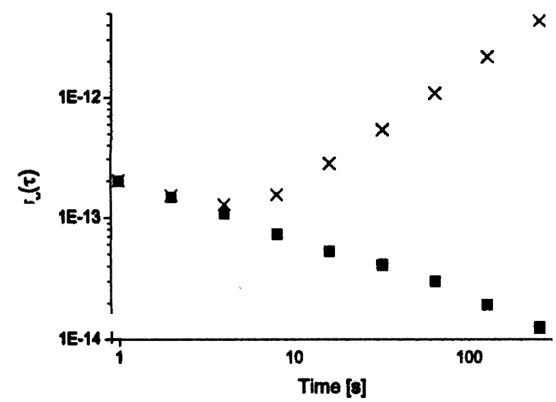


**Fig. 4. Measured relative Allan standard deviation $\sigma_y(\tau)$ of the cavity (×); same data with the linear drift removed(■)**

time scales the drift of the cavity becomes evident. For the measurement shown in fig. 4 the cavity drifts approaches 20 Hz/s, but the drift changes from day to day and can be lower than 3 Hz/s. The details of the strontium experiment, as well as the obtained results are presented in these proceedings in paper Th3C-2 [4].

## IV. Conclusion

Several frequencies have been measured with a frequency comb. For the $I_2$-stabilized Nd:YAG and ultra-stable cavity measurements the (in)stability is currently limited by the intrinsic noise of the frequency comb itself, as well by the stability of the microwave frequency reference. Both these issues are currently being addressed in our laboratory, and we expect an improvement in the short term relative Allan standard deviation by almost an order of magnitude.

## References


[1] T. A. Birks, J. C. Knight, and P. S. J. Russell, "Endlessly single-mode photonic crystal fiber," *Optics Letters*, vol. 22, no. 13, pp. 961–963, 1997.

[2] J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm," *Optics Letters*, vol. 25, no. 1, pp. 25–27, 2000.

[3] G. D. Rovera, F. Ducos, J.-J. Zondy, O. Acef, J.-P. Wallerand, J. C. Knight, and P. St. J. Russell, "Absolute frequency measurement of an $I_2$ stabilized Nd:YAG optical frequency standard," *Meas. Sci. Technol.*, vol. 13, pp. 918–922, 2002.

[4] I. Courtillot et al., "Optical frequency measurements with laser cooled Sr atoms.," *These proceedings.*.