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# Transmission of an optical frequency through a 3 km long optical fiber

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**Abstract.** A 3 km long optical fiber is used to connect two laboratories in Paris. We present the metrological properties of this optical link to transfer an optical frequency standard at 778 nm and we show that the frequency shift introduced by the fiber is only of few Hz.

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## 1 Introduction

Optical frequency measurements are important for metrology, spectroscopy and precision determination of fundamental constants. Such measurements require accurate secondary frequency standard in the visible range. So far, the most widely studied of these has been the iodine stabilized He-Ne laser at $\nu = 473.6$ THz ($\lambda = 633$ nm). More recently, several new optical frequency standards have been developed, for example the iodine stabilized frequency doubled Nd:YAG laser ($\nu = 564$ THz, $\lambda = 532$ nm) [1], the Ca intercombination line at $\lambda = 657$ nm ($\nu = 456$ THz) [2] or the two-photon Rb transition at $\lambda = 778$ nm ($\nu = 385$ THz) [3]. These frequencies have been related to the primary frequency standard, the Cs atomic clock [4–7]. Such measurements need frequency multiplication chain from the Cs clock to the visible range. They are rather complicated experiments which are made in the metrological laboratories. For the metrological or spectroscopic applications, the accuracy of these measurements is transfered to other laboratories by comparing several standard lasers. That requires the carriage of an apparatus which can reduce the accuracy of the comparison.

For instance, several laboratories in Paris collaborate in the domain of the optical frequency metrology. The aim of this work is the high resolution spectroscopy of the hydrogen atom and the determination of the Rydberg constant. In 1992, the absolute measurement of an iodine stabilized He-Ne laser (labelled INM12) from the *Institut National de Métrologie* was performed in the *Laboratoire Primaire du Temps et des Fréquences* (LPTF) [4]. Afterwards, the INM12 He-Ne laser was carried to the *Laboratoire Kastler Brossel* (LKB) to measure the optical frequency of the 2S-8S/D transitions in hydrogen [8]. In a more recent experiment [9], we have avoided the transport of the standard laser thanks an optical fiber to send the reference frequency from one laboratory to the other. We have used the two-photon Rb standard at 778 nm and, in this paper, we describe the metrological features of this optical link.

## 2 Experimental arrangement

Two optical fibers, 3 km long, have been placed between the LPTF and the LKB in Paris. These fibers are singlemode at 1.3 $\mu$m. In our experiment, we work at 778 nm and the fiber are multimode at this wavelength. The transmission is about 10% (including the input losses).

To check the frequency broadening and the frequency shift due to the fiber, we have used either a laser diode stabilized on the Rb two-photon line at 778 nm or a titanium-sapphire laser. Figure 1 shows the experimental set-up. The laser beam is splitted in two paths. One part is sent through one optical fiber to the other laboratory where the two fibers are connected and comes back after a round trip of six km. It is frequency compared with the other part which has been frequency shifted with an Acousto-Optic Modulator (AOM). We use two Si avalanche photodiodes to detect the beat notes before or after the roundtrip in the fibers (photodiode 1 or 2). After amplification, the detection bandwidth is from dc to 1 GHz. The output signals are displayed either on a spectrum analyser or on a frequency counter.

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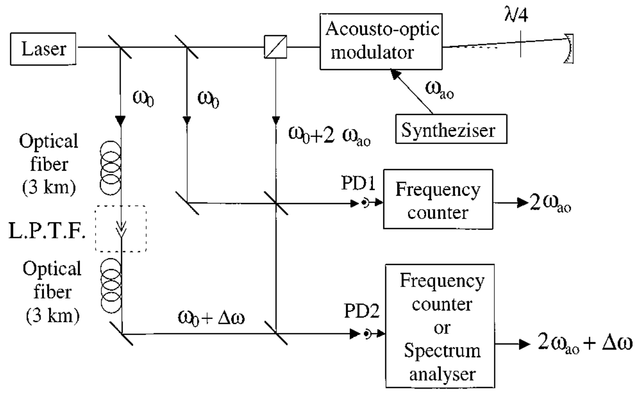


**Fig. 1.** General scheme of the apparatus.

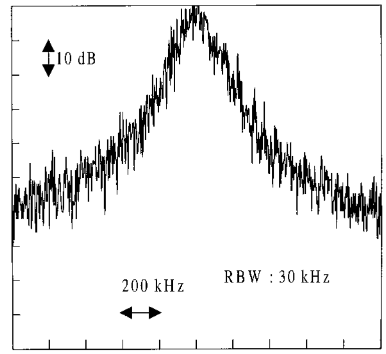


**Fig. 2.** Spectrum analyser recording of the self-heterodyne beat note of the laser diode. The full frequency span is 2 MHz, and the resolution bandwidth is 30 kHz.

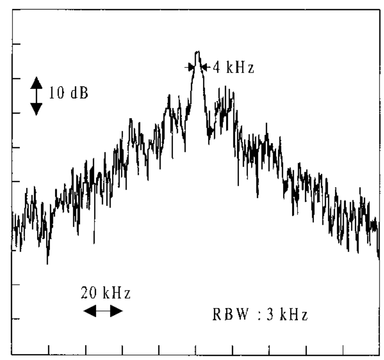


**Fig. 3.** Recording of the self-heterodyne beat note obtained with the titanium-sapphire laser. The full frequency span is 200 kHz, and the resolution bandwidth is 3 kHz. The 3 dB linewidth is about 4 kHz.

## 3 Frequency broadening

We can simply express the electric field $E(t)$ of the laser beam as:

$$E(t) = A\cos[\omega_0 t + \varphi(t)]$$

where $A$ is a fixed amplitude, $\omega_0$ the center frequency and $\varphi(t)$ describes the phase fluctuations (we suppose that $< \varphi(t) >= 0$, where $< \varphi(t) >$ is the mean of $\varphi(t)$). The AC light intensity detected by the photodiode is given by:

$$I(t) = \alpha A^2 \cos\{2\omega_{\rm AO} t + \varphi(t) - \varphi[t - \tau(t)] + \omega_0 \tau(t)\}$$

where $\alpha$ represents the transmission coefficient of the beam splitters and/or of the fiber, $\omega_{\rm AO}$ the frequency shift of the AOM and $\tau(t)$ the delay due to the fiber. When we detect the beat note before the fiber (photodiode 1), $\tau(t) = 0$ and $I(t)$ simply reproduces (with a factor 2) the output of the frequency syntheziser which drives the AOM.

We have measured a time delay $\tau(t)$ of 37.4 $\mu$s for the 6 km round trip. As the fiber is not monomode, this time depends on the propagation mode in the fiber. Practically, we have observed a slight dispersion of this delay: after the fiber, the width of an initial 20 ns light pulse is about 40 ns. Due to the temperature effects, this delay can vary with $t$. It can also fluctuate, depending on the geometrical distribution of the light field between the various propagation modes. When we neglect these variations, $I(t)$ allows to estimate the spectral linewidth of the laser [10]: if the time delay $\tau(t)$ is larger than the correlation time of the laser, the phase $\varphi(t)$ and $\varphi[t - \tau(t)]$ are uncorrelated and the signal $I(t)$ is similar to the beat note between two independant lasers. The resolution of this self-heterodyne method is about $0.6/\tau$ [11], that is to say 16 kHz in our case. Figure 2 shows the spectrum analyser recording obtained with the laser diode. We observe a 3 dB linewidth of about 100 kHz analogous to the jitter of the laser diode. To try to observe the frequency broadening caused by the fiber (due to the fluctuations of the term $\omega_0\tau(t)$), we have used a highly stable titanium-sapphire laser with a frequency jitter reduced to the level of 2 kHz [12]. As, in this case, the coherence time of the laser (approximately 500 $\mu$s) is larger than the time delay of the fiber, the phase $\varphi(t)$ and $\varphi[t - \tau(t)]$ are strongly correlated and the width of the self-beat note would be smaller than that obtained with two independant titanium-sapphire lasers (about 5 kHz, see Ref. [12]). In fact, the width of the observed beat note is approximately 4 kHz (see Fig. 3). This value gives an upper limit of a possible frequency broadening due to the optical fiber.

## 4 Frequency shift

In a second experiment, we have measured the frequency shift induced by the fiber. In this case, the photodiode signal is sent on a frequency counter. The frequency shift due to the fiber is the difference between the beat frequency and the AOM frequency shift $2\omega_{\rm AO}$. Figure 4 shows the results of 1000 1s- measurements. Several periods appear on this figure. During periods (a), we have moved actively the extremities of the fibers in LPTF or LKB. We observe a random frequency shift up to few kHz. It is due to the fluctuations of $\tau(t)$ when we change the geometry of the fiber. On another hand, when the optical fiber is unpertubed (periods (b)), the frequency shift is very small. The histogram of 1000 measurements in these conditions is reported in Figure 5: we observe a frequency noise of about 10 Hz and a shift of few Hz. For these 1000 measurements, the mean shift is only 0.4 Hz. This systematic shift is due to a drift of the time delay $\tau(t)$ which is probably due to

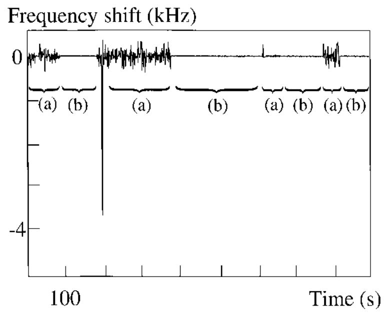


**Fig. 4.** Frequency shift due to the optical fiber ; (a) when the extremities of the fiber are actively moved, (b) when the fiber is not perturbed.

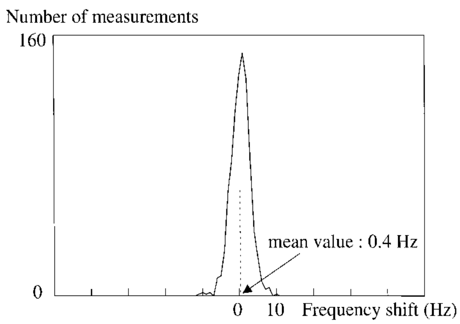


**Fig. 5.** Histogram of 1000 measurement of the frequency shift caused by the fiber. For each measurement, the frequency is counted during 1 s.

a temperature effect. After the fiber, the electric field is:

$$E_{\mathrm{out}}(t) = A_{\mathrm{out}} \cos\{\omega_0[t-\tau(t)] + \varphi[t-\tau(t)]\}$$

where $A_{\mathrm{out}}$ is the field amplitude at the output of the fiber. If we suppose that $<\varphi(t)>=0$, a linear variation of the delay with the time induces a frequency shift $\Delta\omega$:

$$\Delta\omega = \omega_0 \frac{\mathrm{d}}{\mathrm{d}t}[\tau(t)].$$

If we only consider the variation of the refractive index $n$ with the temperature $T$, we obtain:

$$\Delta\omega = \omega_0 \tau(t) \frac{1}{n} \frac{\mathrm{d}n}{\mathrm{d}T} \frac{\mathrm{d}T}{\mathrm{d}t}.$$

For example we obtain that a temperature variation of 0.03 K/hour induces a frequency shift of 1 Hz. Finally, we have studied this systematic shift during several days. The results are reported in Figure 6. The shift is negative or positive, and, at maximum, of few Hz.

## 5 Conclusion

In conclusion, we have studied the frequency shift due to a 6 km optical fiber. Our experiment is very simple, and do not use sophisticated method to cancel the phase noise introduced by the optical fiber, as described in reference [13]. We have shown that it is possible to transfer, without any precaution, an optical frequency with an accuracy of

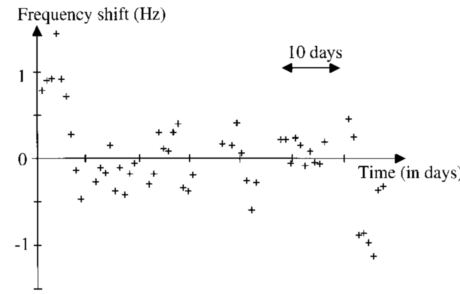


**Fig. 6.** Day-to-day variation of the frequency shift introduced by the fiber. Each point is the mean of about 1000 20 s-measurements.

few Hz, that is to say a relative accuracy better than 1 part in $10^{14}$. This precision is sufficient for the most metrological applications. On the other hand, a phase measurement is not possible, because we do not use a monomode optical fiber. In the future, it will be possible to dispatch a standard laser between different laboratories on a scale of several km.

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