Published in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control
59, 3, 457-462, 2012
which should be used for any reference to this work

Pulsed Optically Pumped Rubidium Clock With High Frequency-Stability Performance

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and Florian Gruet

***Abstract*—In this paper, we present the performance of a vapor-cell rubidium frequency standard working in the pulsed regime, in which the clock signal is represented by a Ramsey pattern observed on an optically detected laser absorption signal. The main experimental results agree with previously reported theoretical predictions. In particular, we measured a relative frequency stability of $\sigma_y(\tau) \approx 1.6 \times 10^{-13}\tau^{-1/2}$ for integration times, τ, up to 200 s, which represents a record in short-term stability for a vapor-cell clock. We also discuss the most important physical phenomena that contribute to this result**

I. Introduction

In recent years there have been several attempts to develop compact vapor-cell atomic clocks with high frequency stability performance. The interest for such devices is motivated by the increasing demand for stable references coming from timing systems (such as satellite radionavigation) and primary frequency metrology, both of which require very stable local oscillators. Several laser-pumped vapor-cell frequency standards working either in the continuous or pulsed regime were demonstrated to be very attractive in this regard [1]–[3]. In particular, we proposed the pulsed optical pumping (POP) technique (see [4] and references therein) that relies on the time separation of the three following phases: 1) preparation of the atomic sample through laser optical pumping; 2) microwave interrogation; and 3) detection of the clock transition.

One of the key properties of this scheme is that the mutual influence of laser and microwave signals is greatly reduced compared with a continuous approach: the clock transition takes place in the dark, when the pumping light is off and the coupling of laser fluctuations to the atomic frequency is negligible. For this reason the pulsed approach turns out to be particularly effective at reducing light-shift effects, compared with other light-shift-free techniques [5]–[7] in which a working point is, in general, found where light-shift is compensated but not fully eliminated, or where the level of compensation might vary in time.

Indeed, the POP approach is also effective at improving upon the short-term stability performance according to the following points: 1) the microwave interrogation is done with a time-domain Ramsey-type technique that produces very narrow clock resonance linewidths (≈100 Hz) which are insensitive to any laser and/or microwave broadening, depending exclusively on the Ramsey time, T; and 2) the laser-induced atomic population inversion can be further increased by a multistep laser-microwave pumping technique [8] with respect to the 30% value typically achieved for ^{87}Rb.

Provided other noise sources are controlled (microwave phase-noise, laser amplitude and frequency noises, etc.), the previous factors contribute to improve the short-term stability through the atomic quality factor and the signal-to-noise ratio.

In the past, we investigated the POP approach in great detail with microwave detection [4]: the magnetization created in the atomic medium by the Ramsey pulses excites a microwave field that can be detected as a maser emission after the second pulse when the atoms are placed in a high-Q cavity (free induction decay signal). This POP Rb maser reached a frequency stability (Allan deviation) of $\sigma_y(\tau) \approx 1.2 \times 10^{-12}\tau^{-1/2}$ [9] for integration times τ up to 10^5 s, and achieves the 10^{-15} region after drift removal, a result comparable to that of a passive hydrogen maser.

Recently, we devoted our attention to the possibility of detecting the clock transition in the optical domain. In this case, the atomic reference is observed on the laser absorption signal at the end of the cell. The laser is then switched on during the detection window, but it is used as a probe: intensity and duration, in principle, differ from those used in the optical pumping process. The interest in using optical detection is motivated by the fact that the signal-to-noise ratio is then shot-noise-limited, resulting in an improvement by more than an order of magnitude compared with the thermal noise that sets the ultimate stability limit of the passive maser approach [9]. In this paper, we provide a characterization of Ramsey fringes observed in the optical detection mode and we report the considerable improvement attained by the POP clock in terms of short-term stability.

II. Setup

The experimental setup (Fig. 1) is based on a microwave cavity-vapor cell arrangement and follows closely

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DOI: http://dx.doi.org/10.1109/TUFFC.2012.2215

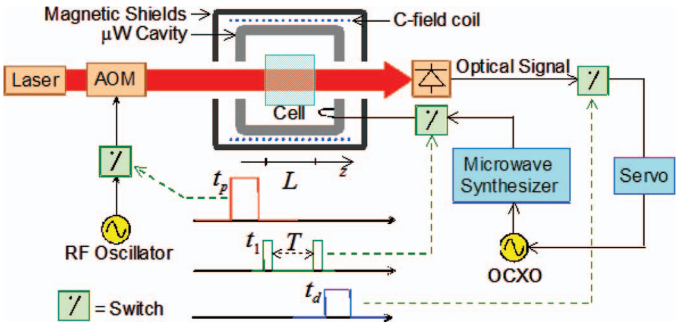

Fig. 1. Schematic setup of the pulsed optical pumping frequency standard. Magnetic field, laser beam propagation direction, and cavity axis are collinear; t_p, t_1, T, and t_d are the pumping, Rabi pulses, Ramsey decay, and detection times, respectively.

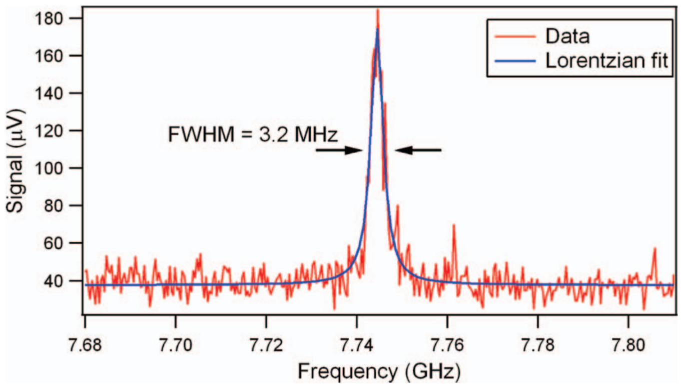

Fig. 2. Beat note measurement of the distributed feedback laser head against a 795-nm external-cavity diode laser.

the description reported in our previous works; however, a new physics package (PP) optimized for the optical detection has been designed and implemented [10].

The core of the PP is a cylindrical quartz cell (20 mm in diameter and 20 mm long) containing a vapor of ^{87}Rb atoms and 25 Torr of buffer gas (a mixture of Ar and N_2 in the pressure ratio $P_{\mathrm{Ar}}/P_{\mathrm{N2}} = 1.6$). The cell is placed in a Mo cavity, sustaining the TE_{011} mode and tuned to the ground-state hyperfine frequency of ^{87}Rb (6.834 GHz); the loaded quality factor is $Q_\mathrm{L} \leq 1000$. The cavity is thermally stabilized and the operating temperature is about 336K. A magnetic field of 1.5 μT is generated by a solenoid to lift the degeneracy of the Zeeman levels. Three μ-metal magnetic shields surround the cavity system. The PP is then placed in a vacuum enclosure to avoid the effects related to environmental fluctuations, such as barometric pressure, humidity, etc. [10], [11]. In particular, barometric pressure is the main limiting factor; through the dielectric constant of air, it causes a fluctuation in the clock frequency of 1×10^{-15}/Pa, quite large a effect for operation in air [10], [12].

The two phase-coherent microwave pulses for the Ramsey interaction are provided by a direct synthesis chain starting from a low-phase-noise 10-MHz oven-controlled crystal oscillator (OCXO) working as a local oscillator (LO). A magnetic loop excites the TE_{011} cavity mode and a Si photodiode monitors the laser absorption signal. The whole electronic system operates in gated mode following the timing sequence of Fig. 1. The low-phase-noise synthesis chain has been designed similarly to that reported in [13], but it has been improved, taking advantage of the use of non-linear transmission lines [14].

The LO is frequency-locked to the Rb clock transition via a digitally implemented lock-in and servo loop. The locking procedure is similar to that of an atomic fountain but much faster [13]. The LO frequency is square-wave modulated between two values on each side of the clock signal (central Ramsey fringe) and the digital servo steers the LO frequency for the same optical detection level on each side.

As pumping sources, we performed experiments with lasers exciting both the D_1 (795 nm) and the D_2 (780 nm) optical lines. Although the best results have been achieved with D_2 line, it is also useful to consider the D_1 line to have some insight into the physics occurring in the cell during the POP operation. In fact, using the D_1 line, we developed a theory in good agreement with the experiment: the two ground-state hyperfine levels and the component $F' = 1$ of the D_1 line excited state are assumed to be a closed three-level system, the other component with $F' = 2$ is separated by more than one homogeneous linewidth. This assumption does not apply to the D_2 line because its hyperfine components in the excited state are mixed together by the buffer gas broadening and the theoretical treatment is not yet fully developed.

The 795-nm pump light is provided by a compact (0.2 dm^3 volume) laser head, similar to a previous design [15], but using a distributed feedback (DFB) laser diode. These lasers show stable, narrow-band single-mode emission while using only one pump-current section. For this laser type, aging of the emission wavelength is reported to be slow enough to allow for 15 or 20 years of clock operation [16]. At the Fourier frequency $f = 300$ Hz, we measured a relative intensity noise (RIN) of 2×10^{-14}/Hz and a frequency noise of 4 kHz/Hz$^{1/2}$. The laser linewidth is found to be ≈3 MHz by beat-note with a narrow-line extended-cavity diode laser, see Fig. 2.

The laser frequency is stabilized to saturated-absorption lines (≈25 MHz linewidth) obtained from a small cell filled with enriched ^{87}Rb. The measured short-term frequency stability of the laser is $\sigma_{y\mathrm{L}}(\tau) \approx 2.4 \times 10^{-11}\tau^{-1/2}$ (see Fig. 3), corresponding to the estimated signal-to-noise limit. The frequency stability at 1 d is 10^{-10} (drift of ≈40 kHz/day), sufficient to control the clock's frequency light-shift below the 10^{-14} level. At the output of the laser head, the beam is sent to the PP through an acousto-optic modulator (AOM) acting as an optical switch to perform the optical pumping and the detection of the clock transition. The beam diameter is 15 mm.

III. RESULTS

Fig. 4 shows Ramsey fringes as observed on the absorption signal [17] and the corresponding theoretical curve.

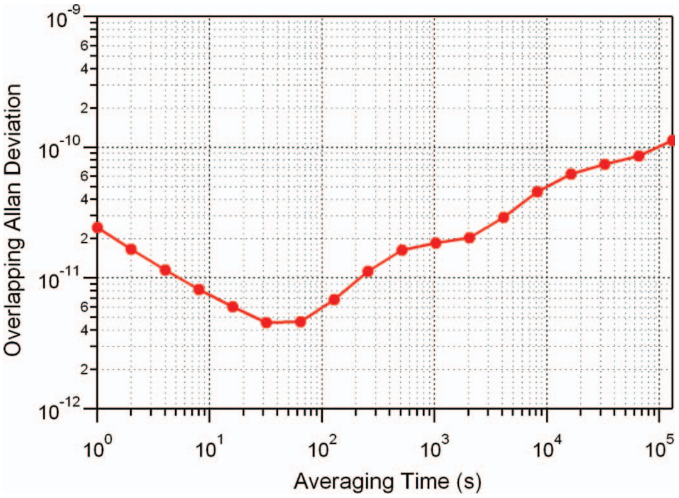

Fig. 3. Allan deviation of the laser frequency stability (beat measurement between two laser systems).

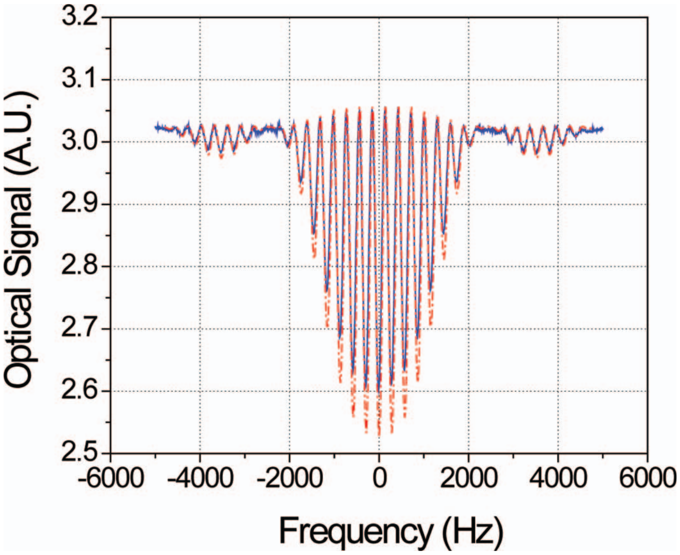

Fig. 4. Comparison between computed (dashed line) and observed (continuous line) Ramsey fringes using the D_1 line for optical pumping; timing: $t_\mathrm{p} = 3.7$ ms, $t_1 = 0.4$ ms, $T = 3$ ms, and $t_\mathrm{d} = 0.15$ ms.

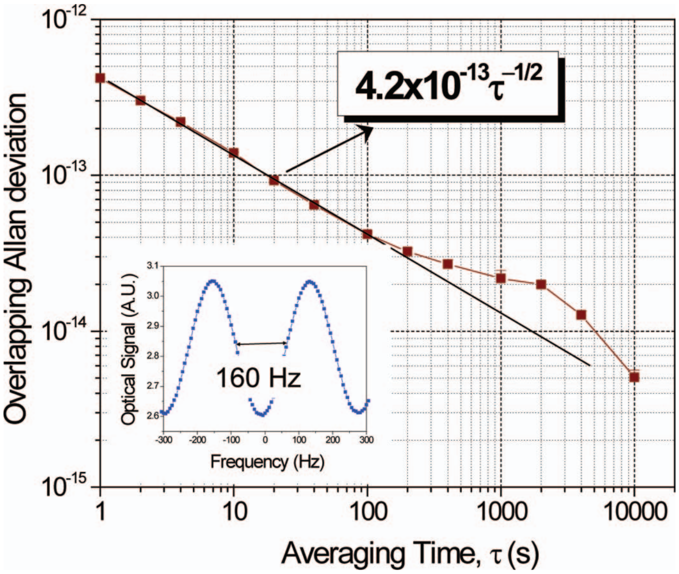

Fig. 5. Frequency stability of the pulsed optical pumping clock with optical detection using D_1 as a pumping line. In the inset, the central fringe of the clock signal is shown.

The laser power is 1.4 mW in the pumping phase and 300 μW in the detection phase. The power of the interrogating microwave is adjusted in such a way that the contrast C of the central fringe is maximized; this corresponds approximately to $\pi/2$ pulses. The theoretical curve has been evaluated according to the theory of [9], but using the values of the parameters corresponding to the present experimental situation. The computed contrast of the central fringe (17%) is in very good agreement with the experimental value (14.5%). The residual discrepancy between the two curves shown in the figure may be related to the fact that in the model we assumed, for simplicity, a uniform laser beam profile, but a Gaussian-shaped laser beam is used in the experiment. This means that the optical pumping process is less efficient at the border of the laser beam, and the clock signal turns out slightly lower than that calculated.

Using this signal as a clock reference, a frequency stability of $\sigma_y(\tau) \approx 4.2 \times 10^{-13}\tau^{-1/2}$ has been measured for τ up to 10 000 s (see Fig. 5).

A linear drift of -2.3×10^{-13}/day has been removed from the data. The bump around 2000 s is due to a periodic fluctuation of the laboratory temperature.

An even better short-term performance is measured with a DFB laser tuned to the D_2 line. The laser bench is similar to that described in [4], but the laser frequency is locked on the level-crossing transition $F' = 1, 2$ of the D_2 line. The laser power during the pumping phase is about 4 mW; during the detection phase, it is 200 μW. Fig. 6 shows the corresponding Ramsey pattern. The contrast of the central line is as high as 28%, mainly resulting from the electric dipole moment of D_2, which is higher than that of D_1.

Fig. 7 shows the frequency stability when the LO is locked on the central fringe of Fig. 6. The short-term stability is $\sigma_y(\tau) \approx 1.6 \times 10^{-13}\tau^{-1/2}$ and the white frequency noise region extends up to 200 s. The slightly degraded stability at $\tau > 300$ s compared with pumping on the D_1 line is mainly attributed to less well-controlled laser intensity.

To individuate the factors limiting the short-term stability, we evaluated the contribution of different noise sources. A similar analysis applies to the result obtained on the D_1 line.

It is well known that the ultimate theoretical stability limit achievable by an atomic clock working in the pulsed regime can be expressed as

$$\sigma_y(\tau) = \frac{1}{\pi Q_\mathrm{a} R}\sqrt{\frac{T_\mathrm{C}}{\tau}}, \qquad (1)$$

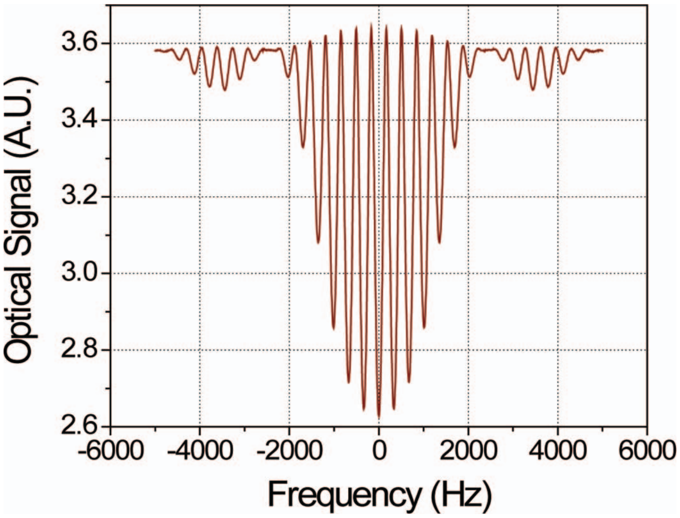

Fig. 6. Ramsey pattern observed on the D_2 line; the central fringe provides the clock signal for the stability measurement reported in Fig. 7; timing: $t_\mathrm{p} = 0.4$ ms, $t_1 = 0.4$ ms, $T = 3$ ms and $t_\mathrm{d} = 0.15$ ms.

where Q_a is the atomic quality factor, R is the signal-to-noise ratio, and T_C is the cycle time. This theoretical limit can be evaluated *a priori* once Q_a and R of the reference atomic transition are known. As previously mentioned, R is related to the shot-noise of the detected photons and can be written as $R = C\sqrt{\eta_\mathrm{q} N^{\mathrm{opt}}}$, where η_q is the quantum efficiency of the detector and N^{opt} is the number of detected optical photons. In the situation of Fig. 6, R is of the order of 49 000 and, accordingly, $\sigma_y^{\mathrm{sn}}(\tau) \approx 1 \times 10^{-14}\tau^{-1/2}$.

As for other passive clocks operating in the pulsed mode, this fundamental limiting value can be degraded by the phase noise of the interrogating microwave: the noise spectral components around even harmonics of the pulse rate are filtered by the atoms and down-converted by aliasing to low-frequency noise (Dick effect [18]). This noise can be expressed as (for $\pi/2$ microwave pulses)

$$\sigma_y^{\mathrm{LO}}(\tau) = \left\{ \sum_{k=1}^{\infty} \mathrm{sinc}^2\left(k\pi \frac{T}{T_\mathrm{C}}\right) S_y^{\mathrm{LO}}(kf_\mathrm{C}) \right\}^{1/2} \tau^{-1/2}, \tag{2}$$

where $S_y^{\mathrm{LO}}(f)$ is the power spectral density of the microwave fractional frequency fluctuations associated with the local oscillator (LO) and $f_\mathrm{C} = 1/T_\mathrm{C}$. $S_y^{\mathrm{LO}}(f)$ has been obtained by measuring the beat note of two nominally identical microwave synthesis chains; in our case, the Dick effect turns out to be $\sigma_y^{\mathrm{LO}}(\tau) \approx 7 \times 10^{-14}\tau^{-1/2}$.

The amplitude fluctuations of the laser probe used to detect the clock signal may further limit the stability achievable by the POP standard. This noise is written similarly to the Dick effect because it is sampled only during the detection time; it turns out to be

$$\sigma_y^{\mathrm{AM}}(\tau) = \frac{1}{CQ_\mathrm{a}} \left\{ \sum_{k=1}^{\infty} \mathrm{sinc}^2\left(k\pi \frac{T}{T_\mathrm{C}}\right) S_y^{\mathrm{AM}}(kf_\mathrm{C}) \right\}^{1/2} \tau^{-1/2}, \tag{3}$$

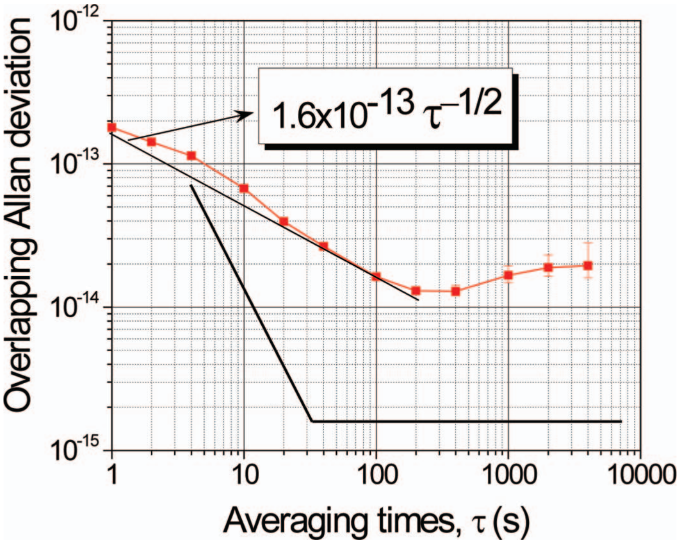

Fig. 7. Frequency stability of the pulsed optical pumping clock using the D_2 line; the bump observed around 4 s is due to the reference signal, provided by a H-maser filtered by a BVA quartz. The thick black line represents the stability of the reference bench.

where $S_y^{\mathrm{AM}}(f)$ is the power spectral density of the fractional intensity fluctuations of the probe signal reaching the photodetector. We point out that this noise contribution scales with the contrast C of the atomic resonance; this means that a high contrast improves the signal-to-noise ratio and at the same time reduces the weight of this noise. In (3), $S_y^{\mathrm{AM}}(f)$ includes both the laser RIN transferred at the output of the cell (AM-AM conversion) and the laser frequency noise converted into amplitude fluctuations (PM-AM conversion) in the detection phase. To gain more physical insight into the role played by these two laser-related noise contributions, we measured the clock frequency stability at 1 s using different dips of the D_2 line to frequency-lock the laser. As shown in Table I, although the contrast appears to be weakly sensitive to the frequency lock dip, the clock stability may change significantly.

We attribute this behavior to the PM-AM conversion, which is sensitive to the slope of the absorption profile. In fact, the level-crossing dip $F' = 1, 2$ is positioned near the maximum of the absorption profile, where the conversion of the laser frequency fluctuations is minimized. For our laser at 780 nm, we have measured $S_y^{\mathrm{AM}}(f) \approx 1 \times 10^{-11}$ Hz^{-1} in the frequency range $f = 100$ to 1000 Hz; (3) then gives $\sigma_y^{\mathrm{AM}}(\tau) \approx 1.1 \times 10^{-13}\tau^{-1/2}$ and this effect is the main limiting contribution to the clock stability for our experimental setup.

IV. CONCLUSIONS

In conclusion, we have implemented a POP clock with a short-term frequency stability of 1.6×10^{-13} at 1 s; this represents a record result for a vapor-cell frequency standard, and is particularly remarkable because it is ob-

TABLE I. Measured Contrast and Standard Allan Deviation Using Different Saturated Absorption Dips to Lock the Laser.

D_2 dip	Contrast C	σ_y ($\tau = 1$ s)
$F' = 2$	26.8%	4×10^{-13}
$F' = 1, 2$	27.5%	1.6×10^{-13}
$F' = 1$	26.8%	4×10^{-13}
$F' = 0$	26.0%	5.5×10^{-13}

tained with a hot atomic sample. This result can be also compared with rubidium clocks developed for the GPS program [19].

As a future perspective, it seems reasonable to further improve this result. In fact, the amplitude fluctuations of the laser probe signal are mainly related to the laser power supply; an improvement of 6 dB in its noise level would lead to $\sigma_y^{\mathrm{AM}}(1\ \mathrm{s}) \approx 6 \times 10^{-14}$. Moreover, considering the state-of-the-art and the spectral characteristics of ultra-low-noise 100-MHz quartz oscillators and properly adjusting the timing sequence, the Dick contribution can be reduced to $\sigma_y^{\mathrm{LO}}(1\ \mathrm{s}) \approx 3 \times 10^{-14}$. Taking the shot-noise limit into account also, the overall frequency stability can reach 7×10^{-14} at 1 s, a value that would position the POP clock as a preferential microwave flywheel in many technological applications. The medium-to-long-term frequency stability may be improved in such a way to be compatible with the previously discussed short-term white frequency noise stability following the guidelines discussed in [10]; this will be discussed in a forthcoming paper.

Acknowledgments

We thank E. Bertacco (INRIM) for his invaluable help; M. Pellaton for filling the Rb cells; and G. Mileti, T. Bandi, P. Scherler, and J. DiFrancesco (all LTF) for their contributions.

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Between 1980 and 1990, at IEN, he developed the Mg beam frequency standard in the 600-GHz region. His research activity also includes the development of techniques for the extension of high-resolution frequency measurements up to the infrared region, and since 1990, the development of highly stable frequency standards.

Currently, his main research interest is in the realization of laser-pumped and coherent population trapping (CPT)-based cell frequency standards and in the realization and maintenance of primary frequency standards. He is now research director and head of the IEN Time and Frequency Division.

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