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# Experimental Demonstration of a Compact and High-Performance Laser-Pumped Rubidium Gas Cell Atomic Frequency Standard

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***Abstract*—The authors present a compact high-performance laser-pumped Rubidium atomic frequency standard exploiting the advantages of laser optical pumping for improved stability. The clock is based on an industrial Rb clock with the lamp assembly removed and optically pumped by light from a compact frequency-stabilized laser head. The modification of the buffer gas filling in the clock resonance cell reduces instabilities on medium-term timescales arising from the ac Stark effect and temperature variations. The frequency stability of the demonstrator clock was measured to be better than $4 \times 10^{-12}\tau^{-1/2}$ up to $10^4$ s, limited by the local oscillator (LO) quartz and RF loop electronics. Long-term drifts under atmosphere amount to $2-6 \times 10^{-13}$/day only, comparable to or lower than that for lamp-pumped clocks under similar conditions. Typical signal contrasts lie at around 20%, corresponding to a shot-noise limit for the short-term stability of $2 \times 10^{-13}\tau^{-1/2}$. The results clearly demonstrate the feasibility of a laser-pumped Rb clock reaching $< 1 \times 10^{-12}\tau^{-1/2}$ in a compact device (< 2 L, 2 kg, 20 W), given the optimization of the implemented techniques. Compact high-performance clocks of this kind are of high interest for space applications such as telecommunications, science missions, and future generations of satellite navigation systems [GPS, global orbiting navigation satellite system (GLONASS), European satellite navigation system (GALILEO)].***

***Index Terms*—Atomic clocks, laser optical pumping, laser stabilization, microwave spectroscopy, satellite navigation systems, semiconductor lasers.***

## I. Introduction

OPTICALLY pumped gas cell atomic frequency standards (often referred to as Rubidium clocks) [1] represent a well-established type of secondary frequency reference, which offers competitive frequency stabilities up to medium-term timescales ($\sim$ days) in compact volumes around 0.25 to 2 L. Industrial realizations of such clocks find applications in telecommunications, as local frequency references, and in space applications like satellite navigation systems [2]. Over the past few years, a number of studies [3]–[12] have been conducted on laser-pumped gas cell frequency standards with the aim of improved frequency stability performance compared to their lamp-pumped counterparts. The narrow and precisely controllable emission spectrum of laser diodes guarantees highly efficient optical pumping, without the need for isotopic filtering of the pump light necessary in lamp-pumped devices. Thus, double resonance signals from clocks using laser optical pumping typically exhibit narrower linewidths $\leq 1$ kHz and higher signal contrasts of around 20% or more, compared to lamp-pumped Rb clocks whose typical values are around 1–2 kHz and 1%, respectively, at best. Therefore, laser optical pumping can offer superior short-term clock stabilities $\leq 3 \times 10^{-13}\tau^{-1/2}$ [6], [9], as well as high-medium and long-term stabilities [10], equaling or surpassing lamp pumping technology when drifts due to thermal- or light-shift [13], [14] effects are controlled. Thus, it offers the potential to realize improved high-performance gas cell clocks while maintaining the advantageous compact design. Moreover, the overall power consumption could be reduced, as laser pumping avoids the high-operating temperature and RF plasma excitation needed for discharge lamps.

In this paper, we report on the demonstration of a compact and high-performance laser-pumped Rb clock with a frequency stability of $3 \times 10^{-12}\tau^{-1/2}$ up to $10^4$ s and the potential to reach the goal of $\leq 1 \times 10^{-12}\tau^{-1/2}$ and down to $1 \times 10^{-14}$ at integration times $\tau \geq 10^4$ s. Such frequency stabilities from an instrument with a volume $\leq 2$ L, a mass $\leq 2$ kg, and a power consumption $\leq 20$ W are of high interest for, e.g., space applications such as satellite navigation systems. Possible future stability improvements based on wall-coated resonance cells [15], [16], low phase-noise microwave sources [17], or schemes for still higher signal contrast [18] finally might lead to novel "super" local oscillators (LOs) with short-term stabilities around $2 \times 10^{-13}\tau^{-1/2}$ to $2 \times 10^{-14}\tau^{-1/2}$ for use in primary atomic clocks.

## II. Clock-Realization Outline

To develop the clock demonstrator, two main issues had to be addressed: the realization of a laser pump-light source showing a sufficient frequency and intensity stability to reach the short-term-stability goal, and the mastering of long-term frequency drifts of the atomic reference. Such long-term drifts arise mainly from the temperature coefficient of the resonance cell and light-shift effects under conditions of laser pumping;

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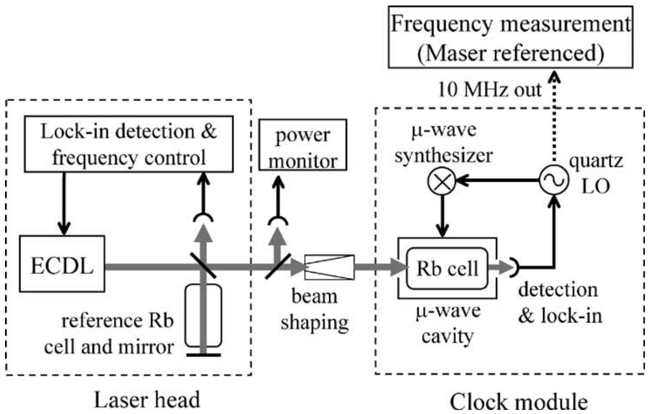


Fig. 1. Functional diagram of the laser-pumped Rb clock.

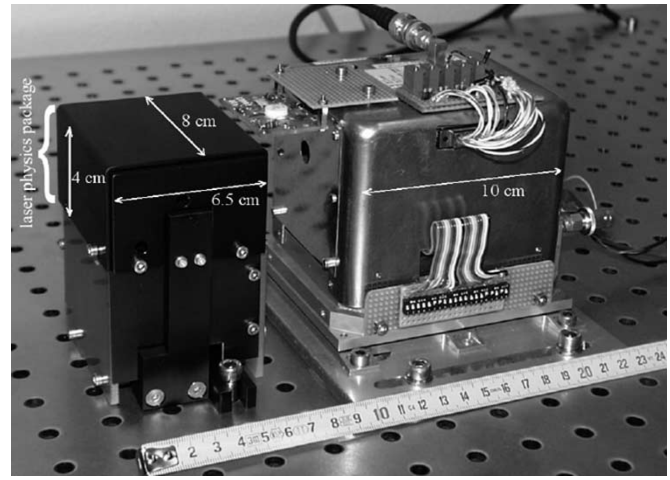


Fig. 2. Photograph of the laser-pumped Rb clock composed of the stabilized laser head (left) and the clock module (right).

both can be controlled by a fine-tuning of the cell's buffer gas content. The clock is composed of a modified industrial Rb clock and a separate laser head as the pump-light source. This modular approach allowed us to independently optimize the performance of both subcomponents, bearing in mind the full integration of the laser head into the clock.

The laser head consists of a compact extended-cavity diode laser (ECDL), frequency-stabilized to Rb absorption lines from a small (2 $cm^3$) reference cell [19]. The laser frequency is stabilized to either the $F = 1$ or $F = 2$ component of the $^{87}$Rb $D_2(5S_{1/2} \rightarrow 5P_{3/2})$ transition for the efficient optical pumping of the $5S_{1/2}$ ground state population of $^{87}$Rb atoms contained in the clock module's resonance cell. In the clock module, the hyperfine ground-state "clock" transition ($F = 1$, $m_F = 0 \rightarrow F = 2, m_F = 0$) at 6.8 GHz is probed by applying a microwave field to the clock cell via a $TE_{011}$ magnetron-type resonator [20]. A 10-MHz quartz LO is stabilized to the center of this double-resonance signal using frequency modulation of the microwave and lock-in detection techniques (Fig. 1).

For the clock module we used an industrial Rb atomic clock [Temex Neuchâtel Time, Rubidium atomic frequency standard (RAFS) type], showing lamp-pumped short-term stabilities of $3 \times 10^{-12}\tau^{-1/2}$ [21]. Applied modifications consisted mainly of the removal of the Rb lamp and related electronics to give a direct optical access to the clock resonance cell, while the quartz LO was exchanged to allow for a wider tuning range during clock optimization. To adapt the clock for laser pumping, the resonance cell's buffer gas content was optimized, as discussed in Section IV. Fig. 2 shows a photograph of the demonstrator clock comprised of its two subunits. In the following sections, the critical aspects of the two subunits will be discussed.

## III. Stabilized Laser Source

The laser head consists of a compact (54 $cm^3$) external-cavity diode laser (ECDL) in the Littrow configuration [19]. Its emission linewith is sufficiently small to resolve the natural homogeneous linewidth around 6 MHz of Rb sub-Doppler saturated absorption lines and allows one to study experimentally the influence of the laser linewidth and frequency noise on the clock's stability [9] by artificially broadening the laser spectrum. The laser head also includes a compact saturated absorption setup for laser frequency stabilization to a temperature-controlled and magnetically shielded Rb reference cell. This reference set-up uses a simple retro-reflected beam geometry without subtraction of the Doppler background and assures a sufficiently robust and precise stabilization of the laser frequency.

The laser head has an overall physics-package volume of 200 $cm^3$ (upper part on the left-hand side in Fig. 2) and to our knowledge today constitutes the most compact stabilized ECDL source containing an integrated reference cell. The volume of the laser head should still be significantly reduced when advanced intrinsically single-mode laser diodes like, e.g., distributed feedback (DFB) or distributed Bragg reflector (DBR) are implemented, since these require no external diffraction grating. Suitable laser diodes of such types at the required wavelengths with sufficiently high output powers and narrow spectral widths have recently started to become commercially available. Thus, there are excellent perspectives for further miniaturization of high-stability diode-laser sources.

### A. Stabilization Reference Spectroscopy

Comparative studies of laser frequency stabilization to Rb absorption lines have shown that even simple and compact realizations of sub-Doppler saturated absorption schemes as implemented in our laser head can guarantee frequency stabilities of $\leq 10^{-12} (< 1$ kHz$)$ at integration times of $\tau \geq 10^3$ s [22], which are required for a high-stability atomic clock unless more elaborate schemes for light-shift suppression are implemented. The still simpler, more robust and compact stabilization to Doppler-broadened absorption lines only offers frequency stabilities roughly one order of magnitude worse, which is insufficient for a high-performance clock. However, it can still suffice in ultra-compact gas cell clocks with lower stability requirements [7], [23], or clocks showing reduced sensitivity to light-shift effects based on optical pumping [24], [25], or the Coherent Population Trapping (CPT) scheme [26], [27].

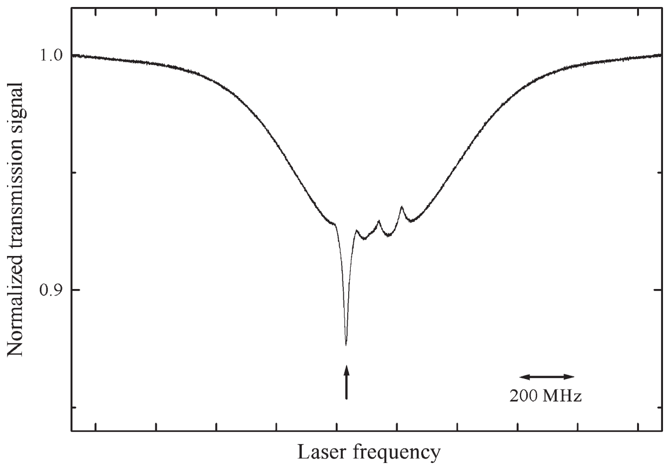


Fig. 3. Laser frequency scan across the $^{87}$Rb $F = 1$ hyperfine transition saturated absorption spectrum from the laser head's reference cell. The arrow indicates the "inverted" sub-Doppler crossover $F = 1 \rightarrow \{F' = 0, F' = 1\}$ resonance that allows for the unambiguous line identification.

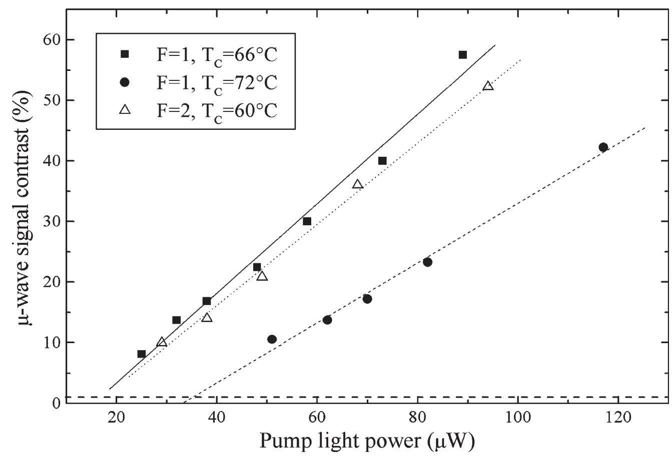


Fig. 4. Contrast of the double-resonance signal (the amplitude of the resonance line divided by the dc-level out of the resonance) for different cell temperatures $T_C$ and optical pumping on the $F = 1$ and $F = 2$ hyperfine components. The dashed line indicates the typical signal contrast in lamp-pumped Rb clocks.

While digital electronic systems for automated line detection and locking of ECDLs can identify the desired sub-Doppler resonance among the multitude of alkali $D_2$ resonance lines [28], a simpler scheme possibly based on analog electronics is clearly preferable for an instrument destined to be space borne. We have identified a narrow inverted sub-Doppler line on the $^{87}$Rb $F = 1$ hyperfine component, which can be unambiguously identified even with a simple control loop. This single "inverted line" (marked by the arrow in Fig. 3) is situated at the frequency of the crossover resonance $F = 1 \rightarrow \{F' = 0, F' = 1\}$ and arises from competition between optical pumping processes under suitably chosen experimental conditions [29], [30]. With the laser locked to this line, the pump-light frequency is also close to the center of the $F = 1$ transition in the clock resonator cell, where intensity-related light-shift effects are small (see Section IV-B). Thus, optical pumping on the $F = 1$ component is promising, in spite of its somewhat lower transition rate compared to the $F = 2$ component. The weaker light absorption on this transition also favors a strong signal transmission through the clock resonance cell while maintaining an elevated cell temperature ($> 60\ ^\circ$C).

### B. Experimental Results

The laser head emits about 2 mW of output power within a spectral width FWHM $< 500$ kHz and exhibits a mode-hop-free tuning over up to 9 GHz, making it well-suited for optical pumping in the Rb clock. A frequency noise of $2\ \text{kHz} \times \text{Hz}^{-1/2}$ and an intensity noise RIN $\approx 10^{-13}$/Hz (at about 300 Hz) measured for the stabilized laser are compatible with the requirements to reach short-term clock stabilities around $2 \times 10^{-13}\tau^{-1/2}$ [6]. The laser stabilization to the integrated reference set-up assures a sufficiently robust and precise stabilization of the laser frequency to a level of $2 \times 10^{-12}\tau^{-1/2}$ up to 100 s and $< 2 \times 10^{-12}$ between $10^2$ and $10^5$ s [22]. The laser routinely stays locked to the internal reference cell over many weeks, thus allowing a long-term operation and evaluation of the clock. Passive drifts of the laser intensity amount to around $2 \times 10^{-4}$ at $10^4$ s, probably arising from thermal gradients and instabilities in the laser head. Here, improvements can be expected from a further miniaturization of the laser head by the implementation of advanced single-mode laser diodes, miniaturized reference cells, or active intensity stabilization.

## IV. Clock Resonance Cell Properties

In this section, we discuss the main relevant properties of the clock resonance cell, which affect the clock stability under laser optical pumping. While the obtained signal contrast and noise levels limit the short-term frequency stability, limitations arising from the light shift are small there and become significant only for the long-term stability, as is the case for the temperature coefficient of the buffer gas cell. We control clock instabilities arising from this temperature coefficient and intensity-related light-shift effects by choosing an appropriate mixture and absolute pressure of buffer gases for the resonance cell.

### A. Double Resonance Signal

Fig. 4 shows the double resonance signal contrast obtained for laser pumping on the $F = 1$ and $F = 2$ optical transitions at selected cell temperatures. With typical incident light intensities around $30-60\ \mu\text{W/cm}^2$ signal contrasts around 15–20% are obtained, while the resonance linewidths range from 0.5 to 1.5 kHz, depending on the microwave power levels. From these measured double resonance signals we derive the shot-noise limit for the short-term stability to be around $5 \times 10^{-14}\tau^{-1/2}$ using the formalism of [31]. An alternative method based on the achievable discriminator slope [6] gives a shot-noise limit of $2 \times 10^{-13}\tau^{-1/2}$. Using this second approach and taking into account the measured laser noise and present quartz stabilization duty cycles, a short-term-stability limit of around $1 \times 10^{-12}\tau^{-1/2}$ is found.

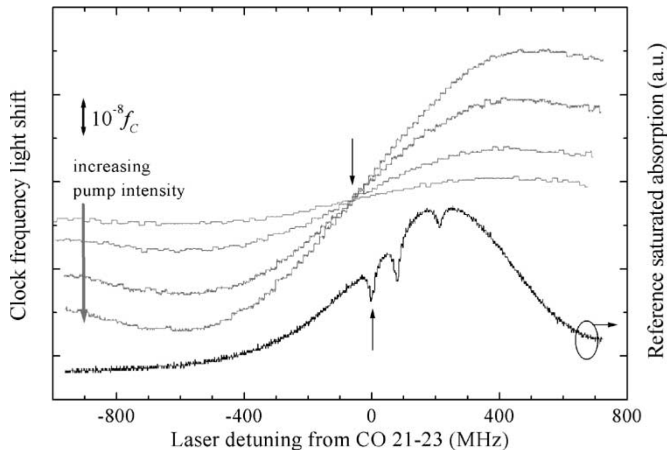


Fig. 5. Measured light shift of the clock frequency $f_C$ in the lamp-optimized resonance cell for different pump light intensities between 10 and 65 $\mu$W/cm$^2$ (upper four traces) and reference saturated absorption from the laser head's evacuated Rb cell (lower trace) for the laser tuned around the $^{87}$Rb $F = 2$ transition.

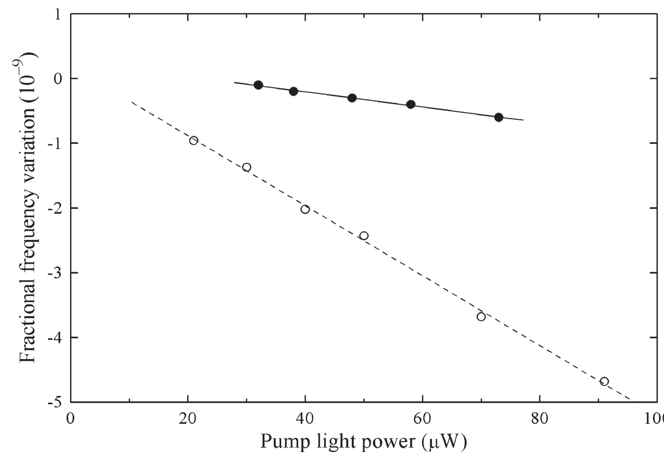


Fig. 6. Intensity-dependent light shift of the ground-state hf transition as function of the pump-light power, measured with the laser frequency stabilized close to the zero LS point on the $F = 1$ component. ○: initial lamp-optimized cell. ●: cell adopted for laser pumping with $\alpha$ reduced by one order of magnitude. The pump beam cross section was 0.8 cm$^2$.

### B. Light Shift

The ac Stark shift or "light shift" of the clock transition induced by the pump light field [13], [14] constitutes a major source of instabilities in optically pumped atomic clocks [5], [8]. In the case of low pump light intensities present in optically pumped clocks, the interaction between the light field and the atomic levels causes the clock transition frequency $f_C$ to exhibit a dispersive shape as a function of the pump-light laser frequency $\nu_L$. While in a buffer gas cell, optical transitions in general exhibit a Voigt profile; the light shift can still be approximated by a dispersive Lorentzian of width $\Gamma$ centered at the pumped atomic transition $\nu_0$ [24]

$$\Delta f_C = \frac{1}{4}|\Omega_R|^2 \frac{(\nu_L - \nu_0)}{(\nu_L - \nu_0)^2 + \frac{\Gamma^2}{4}} \tag{1}$$

where the amplitude of the curve scales approximately linearly with the light intensity $I \sim |\Omega_R|^2$. Fig. 5 illustrates this behavior of the clock frequency, measured for the pump laser frequency tuned across the $^{87}$Rb $F = 2$ transition component using four different pump light intensities. At the intersection point of the four light-shift curves (downward arrow in Fig. 5), variations of the clock frequency with light intensity are minimized, thus the parameter

$$\alpha = \left.\frac{\partial f_C}{\partial I}\right|_{\nu_L = \mathrm{const}} \tag{2}$$

(corresponding to the splitting of the light-shift curves for different light intensities) is small and clock frequency instabilities due to fluctuations of the laser intensity are reduced. Simultaneously, fluctuations in the laser frequency are translated into clock instabilities by the slope

$$\beta = \left.\frac{\partial f_C}{\partial \nu_L}\right|_{I = \mathrm{const}} \tag{3}$$

of the light-shift curves close to line center, requiring the excellent frequency stability of the pump laser.

By adjusting the total buffer gas pressure in the resonance cell to around $P \approx 27$ mbar, we shift the frequency of the optical pump transition, and thus, the point of $\alpha = 0$ in the resonator cell with respect to its unperturbed value [32] so it coincides—within few megahertz—with the reference absorption line in the evacuated Rb cell used for laser stabilization (crossover CO 21–23, upwards arrow in Fig. 5). In this way, the value of $\alpha$ is minimized, which avoids the need for the active stabilization of the pump light intensity. Fig. 6 shows typical pump intensity related shifts of the clock frequency. For typical pump-light levels ($\approx 40\ \mu\mathrm{W/cm^2}$) and with $\alpha$, $\beta$ expressed in the fractional stability of $f_C$, we then have $\alpha \approx 2 \times 10^{-10} \Delta I/I$ and $\beta \approx 3 \times 10^{-17}$/Hz (with almost identical values for pumping on the $F = 1$ and $F = 2$ transitions). Note that with the total buffer gas pressure $P$ fixed such as to obtain a low $\alpha$ value, it is no longer possible to increase $P$ in order to reduce $\beta$. However, higher buffer gas pressures also would result in reduced signal contrasts, which is incompatible with the goal of a high-stability clock.

With the measured stability of the laser source, the short-term clock stability limitations arising from the light shift amount to $\leq 1 \times 10^{-13} \tau^{-1/2}$ for both the laser intensity and frequency related contributions. At $10^4$ s, the fractional laser intensity and frequency stabilities obtained with the simple saturated absorption stabilization implemented in the laser head are $2 \times 10^{-4}$ and $2 \times 10^{-12}$ [22], resulting in clock frequency-stability limits of around $4 \times 10^{-14}$ and $2{-}3 \times 10^{-14}$, respectively. The further reduction of these limits down to around $10^{-14}$ at $10^4{-}10^5$ s can be expected from fine adjustments of the clock cell's buffer gas composition, of the pump light intensity and its fluctuations, as well as from improved laser frequency stabilization or the implementation of schemes for light-shift suppression [24], [25].

### C. Temperature Coefficient

The use of pure buffer gases causes a linear shift of the atomic clock transition frequency with cell temperature,

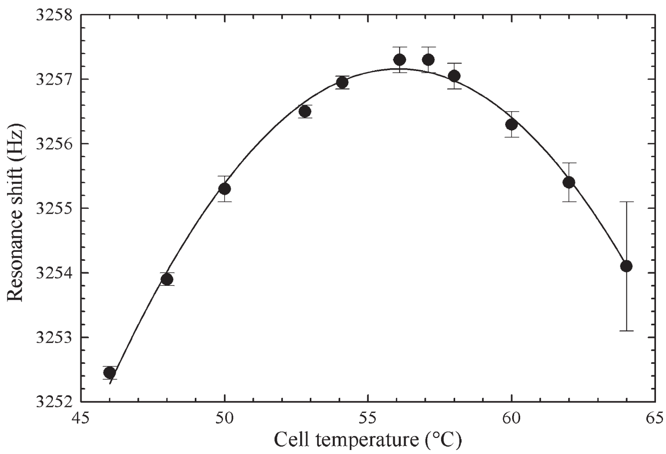


Fig. 7. Temperature dependence of the $^{87}$Rb ground-state hyperfine splitting in the clock resonance cell filled with a buffer-gas mixture.

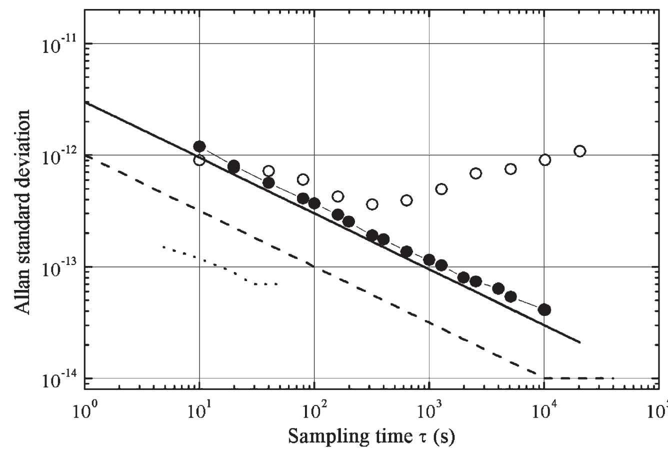


Fig. 8. Frequency stability performance of the clock demonstrator. ○: initial, lamp-optimized cell; ●: cell adapted for laser pumping; solid line: $\sigma_y = 3 \times 10^{-12}\tau^{-1/2}$ (clock module performance); dashed line: $\sigma_y = 1 \times 10^{-12}\tau^{-1/2}$ signal-to-noise short-term limit and clock performance goal; dotted line: technology short-term-stability potential as measured in [9].

typically amounting to some $10^{-9}$/K, which contributes to the final stability limit of the clock. Thus, in the clock cell, we use an appropriate mixture of buffer gases, here Ar and N2 with a partial gas pressure ratio of around $P_{\mathrm{Ar}}/P_{\mathrm{N2}} \approx 1.5$. These gases show linear temperature coefficients of opposite signs, which for the mixed buffer gas cell of the clock demonstrator results in the cancellation of the linear dependence on temperature and in a strongly reduced temperature coefficient of a second order only [33]–[35], as shown in Fig. 7 for the realized cell. With an appropriately chosen cell temperature of around 57 °C, the temperature coefficient is reduced to about $10^{-11}$/K, resulting in a clock stability limit of around $10^{-14}$ for a realizable control of the cell temperature at the millikelvin level. Note that in lamp-pumped Rb clocks using the integrated filter technique, the temperature coefficient is closely connected to the light shift, making their independent optimization much more difficult [36].

## V. Frequency-Stability Performance

The frequency stability of the clock was measured under standard laboratory conditions by comparison with a hydrogen maser (Observatoire de Neuchâtel) using a TemexTime Picotime measurement system. First results using a resonance cell with the buffer gas content optimized for lamp optical pumping showed strong drifts due to light-shift- and thermal effects (open circles in Fig. 8). With the buffer gas mixture in the clock cell adapted for laser pumping (filled circles), the medium-term stability is greatly improved and reaches $4 \times 10^{-14}$ at $10^4$ s, which is consistent with the measured light-shift coefficients and laser intensity and frequency stability. At $10^4$ s, the stability of our compact ($\approx 2$ L, not including laboratory-type laser electronics) clock also reproduces the performance of a much larger ($\approx 27$ L) laser-pumped Cs gas cell clock [10]. Thus, our clock demonstrator represents today's most compact laser-pumped gas cell atomic frequency standard reaching this stability level. The frequency drift of the clock typically amounts to $2{-}6 \times 10^{-13}$/day, probably due to residual thermal instabilities in the laser head and residual temperature coefficients of the clock cell. From the low quality factor ($Q_C < 200$) and the high thermal stability of the microwave cavity, instabilities arising from cavity-pulling effects are estimated to $< 1 \times 10^{-14}$ over 1 day, which is negligible here [1], [37]. These drifts are already comparable to or lower than those for lamp-pumped Rb clocks under the same conditions, which indicates a reduced environmental sensitivity.

The measured short-term stability coincides with the $3 \times 10^{-12}\tau^{-1/2}$ of the lamp-pumped RAFS module (solid line in Fig. 8) but does not yet reach the short-term-stability limit of $1 \times 10^{-12}\tau^{-1/2}$ determined from the measured signal-to-noise ratio of the clock signal (dashed line of Fig. 8). This is due to noise contributions from other sources such as the clock module electronics (LO and RF synthesizer). The continued optimization of the clock is envisaged in order to reach a signal-to-noise limited performance and, finally, a short-term stability around $3 \times 10^{-13}\tau^{-1/2}$, which was already demonstrated for a laboratory laser-pumped Rb clock (dotted line in Fig. 8, [9]).

## VI. Conclusion

We have demonstrated a compact and high-performance laser-pumped Rubidium gas cell atomic clock, using simple schemes and few active stabilization elements. The measured frequency stabilities of the clock and its calculated signal-to-noise limit demonstrate the potential of laser optical pumping for the realization of state-of-the-art Rb gas cell atomic clocks for ground and space applications, which still remain very compact instruments with a physics package occupying a volume well below 1 L. In view of the increasing availability of suitable and narrow-linewidth advanced single-mode laser diodes [38], the further miniaturization of the stabilized laser head and, in time, its integration into the clock module are envisaged. This will allow improved thermal stability and, thus, reduced frequency drifts, leading to a high-performance gas cell clock that reaches a stability around $10^{-14}$ over $10^4{-}10^5$ s, with a total volume of only around 2 L.

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