DIODE-LASER PUMPED, RUBIDIUM CELL FREQUENCY STANDARDS

C. Szekely, R. E. Drullinger, F. L. Walls, J. P. Lowe, and A. Novick
Time and Frequency Division
National Institute of Standards and Technology
Boulder Colorado, USA

Abstract

We report on our project to experimentally investigate the limits to the short-term stability achievable in optically pumped, rubidium cell frequency standards. Theory indicates that the atomic limited stability is several orders of magnitude better than what has actually been achieved. The difference is related to the complex spectral output of the lamps used in conventional standards as well as phase noise in the interrogating microwave radiation. Using a novel filter technique, we have built a microwave synthesis chain with phase noise capable of supporting a standard with $\sigma_y(\tau) \leq 4 \times 10^{-14} \tau^{-1/2}$. With extended-cavity, diode lasers we have demonstrated measured line Q and signal-to-noise ratios commensurate with $\sigma_y(\tau) = 4 \times 10^{-13} \tau^{-1/2}$ in a commercial, buffer gas type standard and $\sigma_y(\tau) = 2 \times 10^{-13} \tau^{-1/2}$ in an evacuated, wall-coated cell. Both of these numbers can be improved significantly in a fully engineered and optimized standard.

Key words: rubidium; optically pumped; diode laser

1. INTRODUCTION

Optically pumped, rubidium-cell frequency standards have theoretical, atomic shot-noise-limited, short-term stability that is *several orders of magnitude* better than what is actually achieved. Qualitatively the potential performance can be understood by considering *only* the number of atoms in a cell and how often each of them can contribute to the signal. Take, for example, a 1 cm^3 cell at 50°C. At this temperature the vapor density of rubidium is about 10^{11} cm^{-3} and the spin exchange rate is about 100/s [1]. Thus, we might expect something of the order of 10^{13} "clock" transitions per second and a linewidth of order 100 Hz. This corresponds roughly to a stability of $\sigma_y(\tau) \approx (Q \times S/N)^{-1} \approx 5 \times 10^{-15} \tau^{-1/2}$. Detailed calculations [2] predict similar limits.

The reason for the tremendous difference between potential and achieved performance is, in part, related to the complex spectral output of the lamp used for the optical pumping in all commercial standards. The non-monochromatic nature of the lamp output has two deleterious effects on the short-term stability of the standard. The presence of light that does not directly contribute to the optical pumping adds a background signal and, hence, noise to the detected signal. Additionally, nearly resonant light actually leads to some active depumping, thus limiting the use of the available atoms.

Our preliminary experiments with diode lasers in place of lamps support this argument. The amount of light reaching the detector is typically a factor of 30-100 less than that in the lamp-pumped standards, while at the same time, the "clock" signal in terms of absolute amount of light change at the detector is larger, in some cases by a factor of 10.

In addition to changes in the optical pumping light source, reaching the high stability available in rubidium cell standards will require exceptionally low phase noise in the interrogating microwave radiation [3]. In fact, the requirements are so severe that they cannot be met with state-of-the-art crystal oscillators and noiseless multiplication. Fortunately, however, the requirement is not on broadband noise. The system is most sensitive to noise centered at a frequency twice the modulation frequency either side of the carrier. We have taken advantage of this fact to suggest a special filter with a notch at both the upper and lower $2\omega_m$ sidebands [4]. This will substantially reduce the noise where it counts and allow improved short-term frequency stability.

We report here on our project to investigate the limits to the short-term stability attainable in a rubidium cell type standard when pumped with a diode laser. The use of diode lasers to pump rubidium standards is not a new idea. There have been several previous investigations of short-term stability [5-10]. All have used commercial rubidium standards and solitary diode lasers without explicit AM or FM noise control. None has reported measured stability better than the original lamp-pumped standard. In the work reported here, we have used extended-cavity diode lasers with their inherently lower FM noise. With these lasers, we have been able to show that at least a large part of the theoretical, short-term stability of rubidium cell frequency standards is experimentally achievable in both buffer-gas cells and evacuated, wall-coated cells.

2. EXPERIMENTAL WORK

We have used an extended-cavity, grating feedback laser as the optical pumping source for two different physics packages. The laser operates on the D_1 line (794.9 nm). The cavity length is servo-controlled to lock the laser frequency to a saturated-absorption feature in an external, evacuated ^{87}Rb cell.

The first experiments were done with the same commercial standard used in Ref. 5. The standard uses a TE_{111} cavity, and the cell contains a natural mixture of ^{87}Rb and ^{85}Rb. Because of the presence of ^{85}Rb, we obtained the best optical pumping on the F = 1 to F' = 2 transition. At the normal operating temperature of the standard($\approx$70°C), the relative absorption dip ($\Delta I/I$) was 10% whereas it was

0.04% when pumped with its lamp. The measured short-term stability of the standard, without AM control on the laser, was $4 \times 10^{-12} \tau^{-1/2}$; see Fig. 1. This is a factor of 3 improvement over the performance of the same standard when lamp-pumped. Limitations in the electronics package and restrictions in the physics package prevented further improvements in short-term stability while lack of AM control on the laser resulted in the relatively poor performance beyond 30 seconds. In changing from the lamp to the laser, the light falling on the detector decreased by a factor of 80 while the absolute magnitude of the microwave-induced change in light signal increased by a factor of 3. The microwave resonance linewidth was essentially unchanged.

The second physics package consisted of a TE_{011} cavity and an evacuated, wall-coated cell with ^{87}Rb [11]. The microwave cavity was surrounded by two magnetic shields and the temperature of the cell and cavity could be controlled separately from the rubidium reservoir. The diameter of the spherical cell was about 3.5 cm. The laser beam had an elliptical cross section of about 0.25 cm^2. This device was never operated as a frequency standard because a microwave electronics package with adequate phase noise was not yet available; see discussion section. Rather, the parametric dependence of line Q and signal-to-noise ratio (S/N) with optical power, microwave power, and spin density was investigated. At room temperature and low microwave power, the resonance is a pure Dicke-narrowed, symmetric, Lorentzian line with a FWHM of 87 Hz. However, on heating of the cell and cavity from room temperature to 340 K, the line Q decreased by a factor of about 2. This was attributed to magnetic effects of the heater but the issue is not resolved at this time. The results quoted are for the actually measured linewidth. At a cell wall temperature of 340 K and for rubidium densities ranging from 1.9×10^{10} to 2.6×10^{11} atoms/cm^3 we evaluated the short-term stability dependence on laser at near optimum microwave power; see Fig. 2.

In addition to the work with laser optical pumping, we have obtained two crystal filters with 1 dB on insertion loss at 10 MHz and more than 25 dB attenuation at 10 MHz $\pm$ 75 Hz as shown in Fig. 3. The residual phase noise added by these filters 10 Hz from the carrier is less than -152 dBc/Hz and less than -162 dBc/Hz at the notch frequency. These limits are probably due to the measurement system and not the resonators. Further measurements are planned. We have also fabricated multiplier chains which have residual noise referenced to 10 MHz of -165 dBc/Hz. Together, these components should allow our new microwave synthesizer to support operation of a standard with $\sigma_y(\tau) \leq 3 \times 10^{-14} \tau^{-1/2}$.

3. DISCUSSION

It now seems clear that at least a large part of the stability potential suggested by theory is actually available in a properly engineered, laser-pumped rubidium standard. However, AM and FM noise in the laser as well as phase noise in the microwave radiation must be addressed.

Extended-cavity diode lasers allow solutions to the necessary AM and FM control. Simple, solitary laser diodes have linewidths of the order of 50 MHz, and the output wavelength is an extremely sensitive function of temperature and current: $d\nu/dT \approx 30$ GHz/K and $d\nu/di \approx 3$ GHz/mA. For grating-feedback lasers operating in the high feedback limit, the linewidth is reduced 2-3 orders of magnitude. The tuning with current and temperature is reduced by a similar amount [12]. With the wavelength set by the grating angle and cavity length (a piezo-mounted mirror), the current and temperature become almost free parameters. In our laser, comparatively crude temperature control is used to adjust the band gap and help with mode selection while the laser injection current is used to set and stabilize the laser output power.

AM noise can be easily controlled to the shot-noise limit in these extended-cavity lasers. Only a very small fraction of the laser output power is needed for the microwave-optical double resonance. Half of the laser power can be used as a monitor in a power-stabilization and noise-controlling servo. This allows the laser output to be AM-controlled within 3 dB of the shot-noise limit [13]. If, for example, 1% of the laser power is used to probe the rubidium cell, the shot noise-limited S/N ratio on this beam will be 10 dB less than that for the full output of the laser. Hence, controlling the full laser power within 3 dB of its shot-noise limit insures that the probe beam used in the clock will be shot noise limited.

Microwave radiation with phase noise adequate to support a standard operating with outstanding short-term stability can be generated from a conventional crystal, local-oscillator/multiplier chain if precautions are taken to reduce the noise at the second harmonic of the modulation frequency. We have demonstrated that such a result can be produced with crystal notch filters designed to work at $\pm 2\omega_m$ from the carrier.

4. SUMMARY

We have built a microwave synthesis chain that incorporates a crystal notch filter concept and is capable of supporting operation of a standard with $\sigma_y(\tau) \leq 3 \times 10^{-14} \tau^{-1/2}$. Our optical pumping results are summarized in Table 1 along with those of other researchers. The measured stability of a commercial standard operated with our line-narrowed laser is a factor of 3 better than with its original lamp and is limited by phase noise in the commercial microwave synthesis package. With an AM loop on the laser and our new microwave synthesizer, our measurements indicate that a short-term stability of $\sigma_y(\tau) \approx 4 \times 10^{-13} \tau^{-1/2}$ can be achieved in this standard. Optimizing the physics package for this new system should yield still further improvements. In an evacuated, wall-coated cell in a TE_{011} cavity we have measured line Q and S/N ratios commensurate with a $\sigma_y(\tau) = 2 \times 10^{-13} \tau^{-1/2}$. With improved magnetic field control and a refined AM loop on the laser, we think this can be reduced to $\sigma_y(\tau) \leq 5 \times 10^{-14} \tau^{-1/2}$.

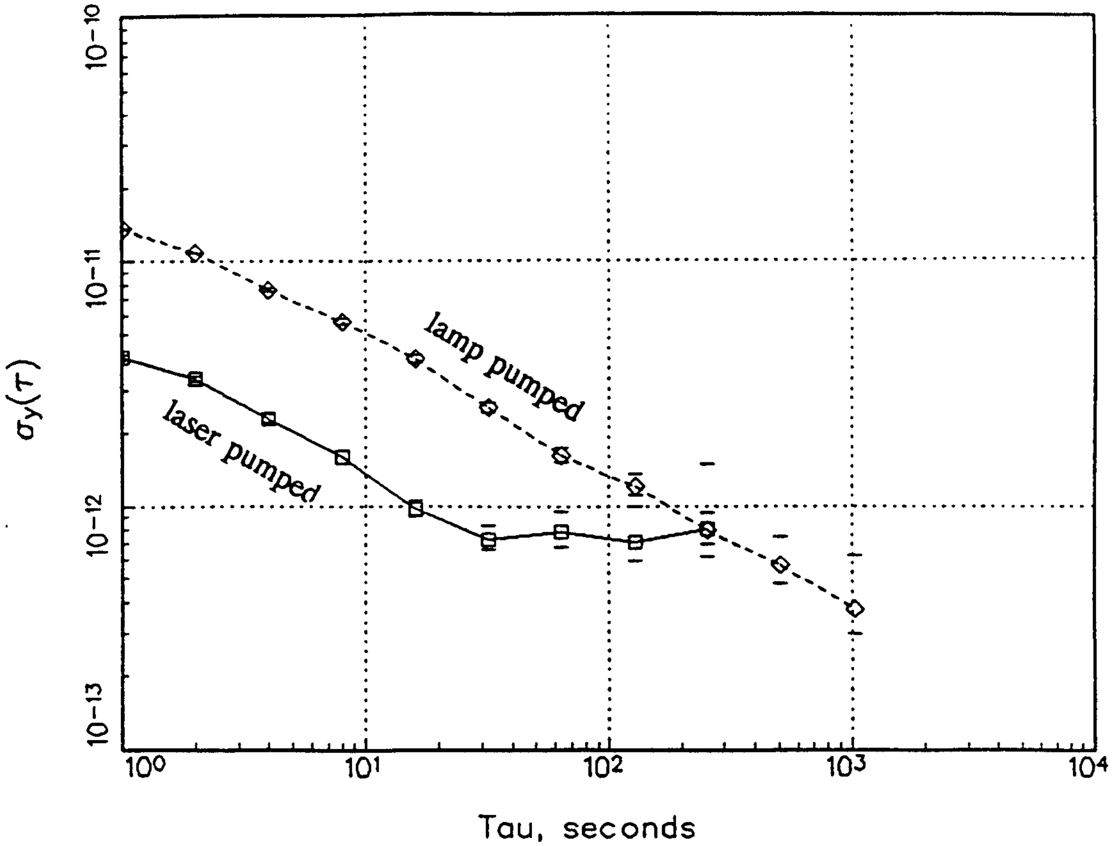

Fig. 1. Frequency stability of commercial standard with lamp pumping and laser pumping. The flicker floor seen in the laser data at times greater than about 20 s is the result of unregulated laser amplitude.

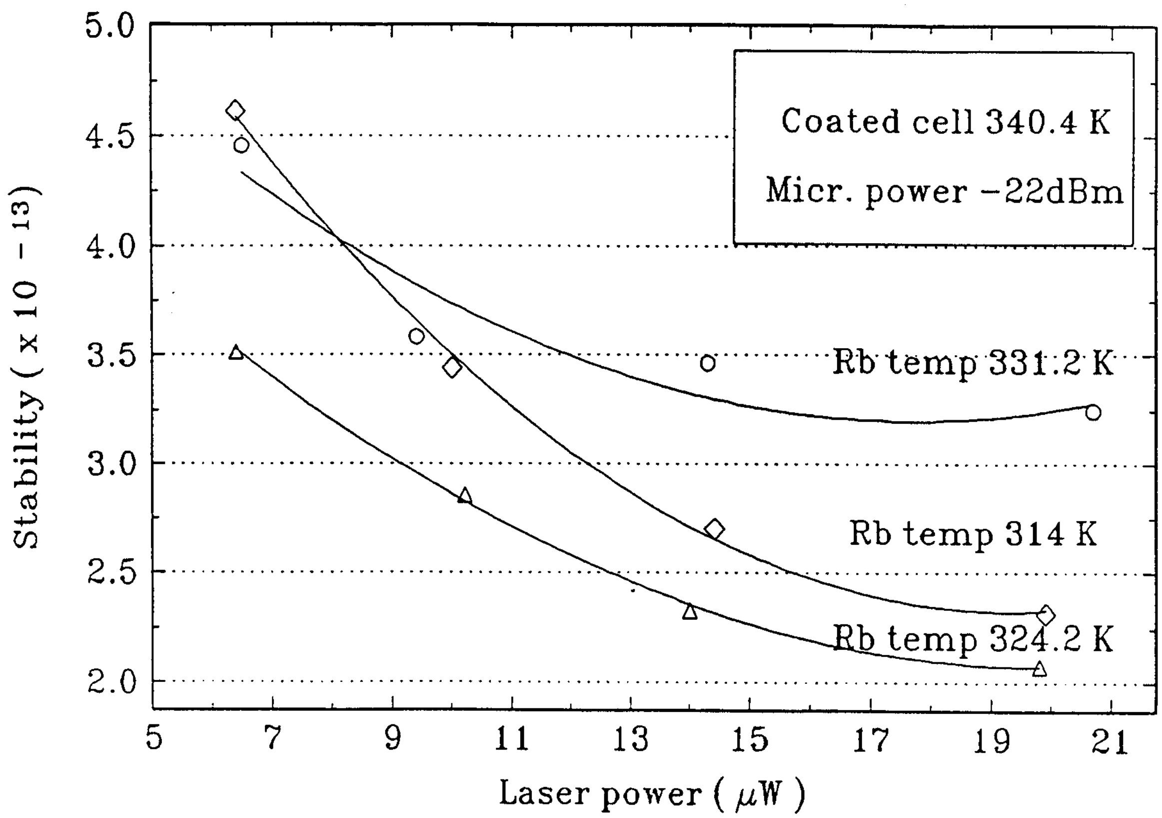

Fig. 2. Evaluated stability for evacuated, wall-coated cell standard. The evaluation is based on experimentally measured parameters and the relationship $\sigma_y(\tau) \cong (1/\nu_0\sqrt{2})(i_n/D)\tau_{-1/2}$ [14].

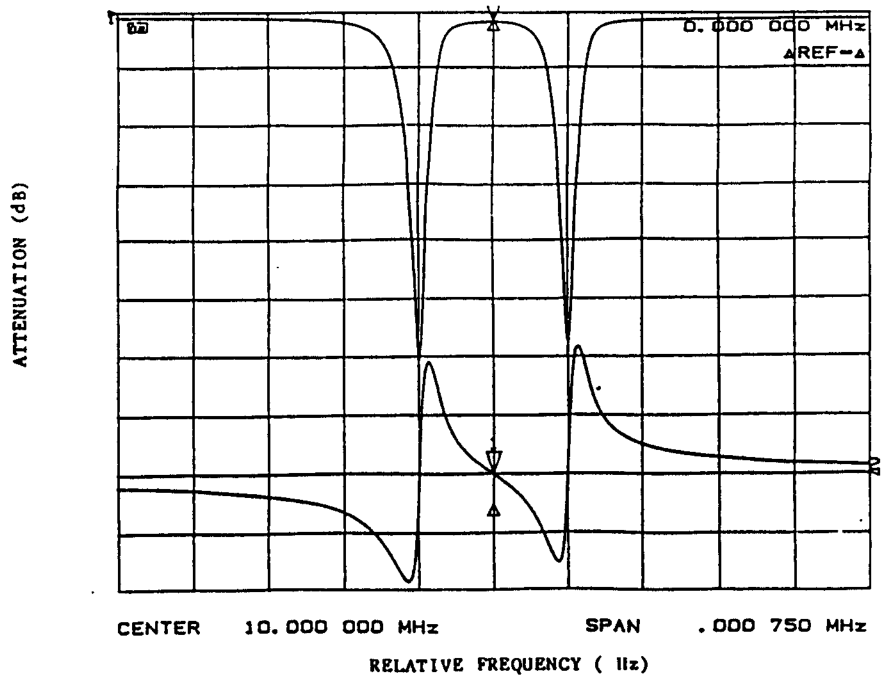

Fig. 3. Transfer function of filter to be used to notch out noise of local oscillator at the $2\omega_m$ sidebands above and below the carrier. The upper trace is the attenuation (5 dB/div) on transmission while the lower curve is the phase shift (50°/div).

Table 1. Summary of experimental results on laser pumped rubidium cell standards.

Source	laser, linewidth, lock technique	cavity and cell type	Measured $\sigma_y(\tau)$	Projected $\sigma_y(\tau)$ based on measured Q and S/N
ref. 5	A	TE_{111}, Buffer gas, Mixed isotopes	$\approx 2 \times 10^{-11}\tau^{-1/2}$ $\tau \leq 100$ s	
ref. 6	B	TE_{111}, Buffer gas, Mixed isotopes	$\approx 10^{-10}\,\tau^{-1/2}$ $\tau \leq 10$ s	
ref. 7	A	Buffer gas, ^{87}Rb		[a] $\approx 2 \times 10^{-11}\tau^{-1/2}$
ref. 8	A	TE_{011}, Buffer gas, mixed & ^{87}Rb		[a] $\approx 3 \times 10^{-12}\tau^{-1/2}$
ref. 10	A	same as ref 8		[b] $\approx 8 \times 10^{-13}\tau^{-1/2}$
this work	C	same as ref 5	$\approx 4 \times 10^{-12}\tau^{-1/2}$ $\tau \leq 30$ s	[c] $\approx 4 \times 10^{-13}\tau^{-1/2}$
this work	C	TE_{011}, Evacuated, wall coated, ^{87}Rb		[d] $\approx 2 \times 10^{-13}\tau^{-1/2}$

A: Solitary laser, D_2 line (780 nm), linear absorption lock, $\Delta\nu_{laser} \approx 40$ MHz
B: Solitary laser, D_2 line, free running frequency, $\Delta\nu_{laser} \approx 400$ MHz.
C: Extended cavity laser, D_1 line (795 nm), saturated absorption lock, $\Delta\nu_{laser} \approx 0.1$ MHz.
[a] Based on measured line Q and S/N combined through the relationship $\sigma_y(\tau) = 0.2/[Q \cdot S/N]$.
[b] Based on measured line Q and S/N combined through the relationship $\sigma_y(\tau) = 0.11/[Q \cdot S/N]$.
[c] Based on measured stability rescaled for available AM noise control in the laser.
[d] Based on measured noise and discriminator slope $[\sigma_y(\tau) \approx (1/\nu_0\sqrt{2})(i_n/D)\tau^{-1/2}]$ [14].

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