DEVELOPMENT OF A CONVENTIONAL LASER-PUMPED RB ATOMIC CLOCK: STATUS REPORT

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Abstract

As is well known, the phase fluctuations of a laser can decrease the signal-to-noise ratio of a vapor-cell clock due to laser PM-to-AM conversion. In previous work, we demonstrated an easy means of eliminating this problem: use high-pressure resonance cells so that collisional dephasing keeps the atoms from following the laser's fluctuating phase. Though our phase-1 clock employing a 100 torr N_2 cell had excellent short-term performance, the long-term performance left much to be desired, quite likely because the increased pressure in the resonance cell gave the clock a fairly large temperature sensitivity. Here, we discuss our progress towards a phase-2 laser-pumped Rb clock, where the temperature sensitivity will be much reduced.

INTRODUCTION

The basic concept of the conventional laser pumped clock **[1]** is to use the light intensity transmitted through an absorbing atomic vapor to generate an atomic signal, and, as is well known, the transmitted light intensity, I(L), follows Beer's Law: $I(L) = I_o e^{-[Rb]\sigma L}$. Here, I_o is the incident laser intensity, [Rb] is the number density of absorbing atoms, σ is the absorption cross section, and L is the length of the vapor. Of course, fluctuations in the intensity of transmitted light will give rise to a reduction in the atomic clock's signal-to-noise ratio, and so transmitted light intensity noise is to be avoided. Transmitted light intensity fluctuations can arise from any one of the terms in the Beer's law expression. Somewhat surprisingly, however, for atomic clock operation, the most important of these is noise arising from fluctuations in σ.

The absorption cross section of an atom is typically thought of as a fundamental atomic feature and, therefore, incapable of variation. While true in the mean, the absorption cross section is actually defined operationally and, therefore, can exhibit fluctuations **[2]**. Briefly, when an atom absorbs laser light, its wavefunction transforms into a linear superposition of ground and excited state wavefunctions: $\Phi = a_g\phi_g + a_e\phi_e$. Since the absorption cross section is defined in terms of the expansion coefficients, a_g and a_e, and since these expansion coefficients depend on the laser's phase, laser phase fluctuations get mapped onto σ and, hence, the transmitted light intensity through Beer's law. In a phrase, the very nature of the field/atom interaction leads to laser phase-noise (PM)-to-amplitude-noise (AM) conversion **[3]**.

Since PM-to-AM conversion is intrinsic to the absorption process, it cannot be eliminated; it can only be mitigated. One means of accomplishing this is to employ diode lasers with very narrow linewidths and, therefore, very low phase noise **[4]**. Another way of mitigating the PM-to-AM conversion process is to make the atoms less sensitive to the laser's fluctuating phase by increasing the rate of collision dephasing. Rapid dephasing collisions interrupt the atoms as they attempt to follow the laser's fluctuating phase, so that the atomic ensemble responds to the average phase instead of its instantaneous values. Though collisional dephasing decreases the atomic line-Q of the 0-0 hyperfine transition, this is more than compensated by the increase in signal-to-noise ratio **[3]**.

THE AEROSPACE LASER-PUMPED CLOCK: PHASE-1

FREQUENCY STABILITY

In our conventional, phase-1, vapor-cell clock, we employed a cleaved-facet diode laser to optically pump a vapor of ^{87}Rb atoms contained with a 100 torr N_2 buffer gas in a TE_{011} microwave cavity **[5]**. Though these lasers are robust and inexpensive, their linewidths are relatively large (~ 30 MHz) and, unfortunately, nearly ideal for PM-to-AM conversion. Nevertheless, based on our understanding of the PM-to-AM conversion process, we expected the short-term stability of our clock to be much improved compared with other laser-pumped clocks that had employed relatively broad-linewidth lasers. These expectations were borne out as illustrated by the data shown in Fig. 1. There, our phase-1 clock's Allan deviation is plotted as a function of averaging time along with results from several other vapor-cell clocks: a NIST clock employing a cleaved-facet diode laser ($\Delta\nu_L$ ~ 30 MHz) **[6]**, a Westinghouse ultraminiature clock employing a VCSEL diode laser **[7]** ($\Delta\nu_L$ ~ 30 MHz **[8]**), one of the best lamp-pumped clocks **[9]**, an improved NIST vapor-cell clock employing a DBR laser ($\Delta\nu_L$ ~ 2 MHz) **[10]**, and an Anritsu clock employing a DFB diode laser ($\Delta\nu_L$ ~ 2 MHz) **[11]**. Clearly, though our short-term performance is quite good, and with a bit of improvement could rival the NIST (DBR) and Anritsu performances, our clock has a very large random-walk frequency noise component.

ORIGIN OF RANDOM-WALK FREQUENCY NOISE

We measured the sensitivity of our clock to various perturbations (i.e., light intensity, laser detuning, microwave power, and temperature). Of these, the clock's temperature sensitivity was relatively the highest: $7.3\times10^{-9}/^{o}C$. This high temperature sensitivity is a direct consequence of the large buffer-gas pressure we employ to mitigate PM-to-AM conversion **[12]**, and suggests that temperature fluctuations of only 10^{-5} to 10^{-4} ^{o}C will limit the clock's frequency stability to 10^{-12} to 10^{-13}.

In order to test this conjecture, we allowed the clock to stabilize for 6 hours without any adjustments and then monitored the temperature for a day and a half. The results of that experiment are shown in Fig. 2a. Using the measured temperature coefficient of the clock, these temperature fluctuations could then be converted to inferred frequency fluctuations and compared with our clock's actual performance. This is shown in Fig. 2b. Clearly, temperature fluctuations drive our clock's long-term frequency instability.

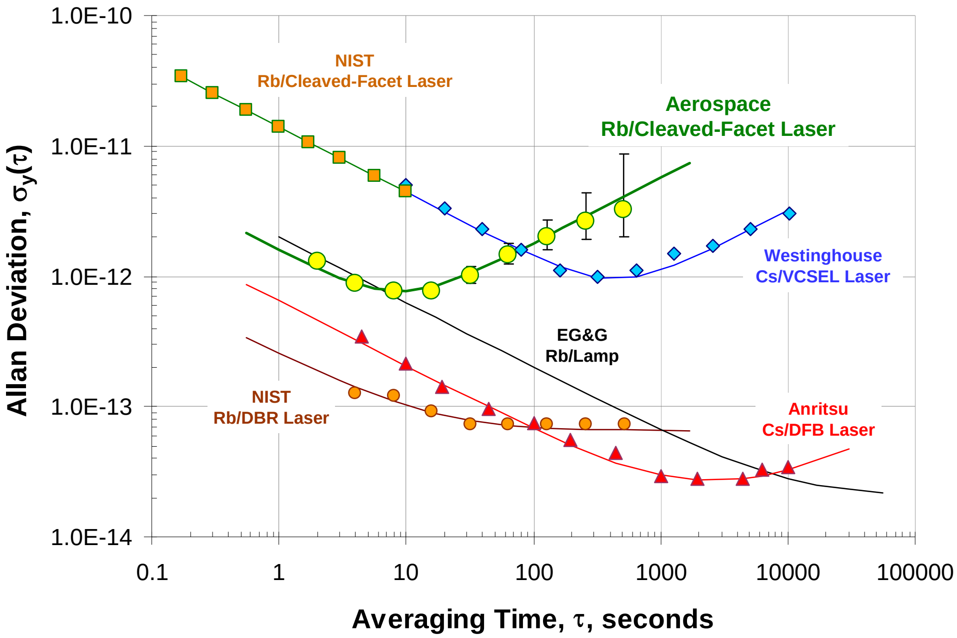

Figure 1. Allan deviation of a number of laser-pumped vapor cell atomic clocks. Using buffer-gas dephasing to mitigate PM-to-AM conversion, our clock's short-term performance is much better than other clocks using broad-linewidth diode lasers (i.e., NIST cleaved-facet and Westinghouse VCSEL). We believe the large random-walk frequency noise of our standard is due to the clock's large temperature sensitivity.

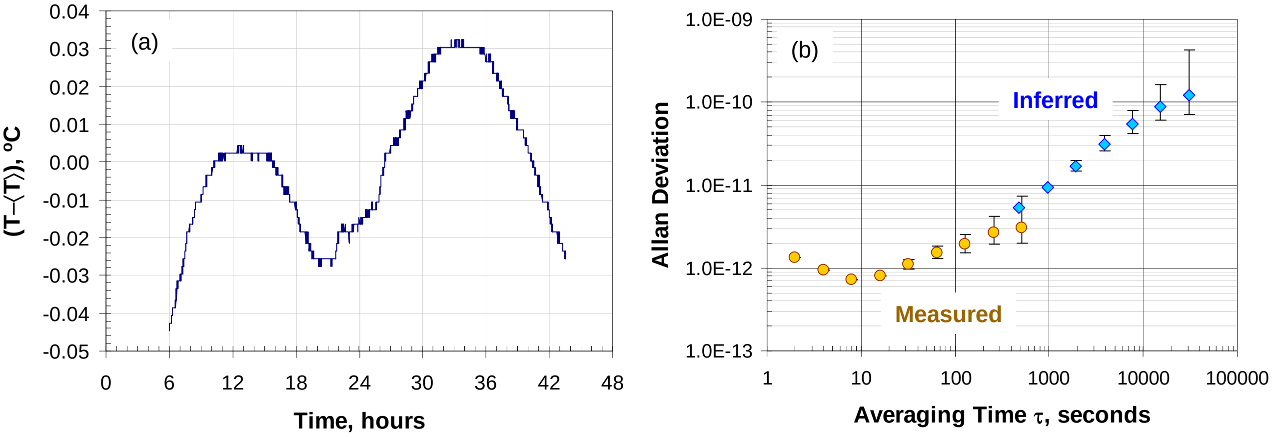

Figure 2. (a) Temperature deviations for our phase-1 laser-pumped Rb clock as a function of time. The discretization of our measurements is apparent. (b) Measured Allan deviation of our phase-1 clock along with the inferred Allan deviation based on the measured temperature fluctuations and our temperature sensitivity. A white phase-noise contribution to the inferred Allan deviation due to the temperature measurements' discretization has been suppressed in the figure.

TEMPERATURE SENSITIVITY OF THE AEROSPACE PHASE-2 CLOCK

In order to mitigate PM-to-AM conversion using rapid collisional dephasing, and at the same time significantly reduce the 0-0 transition's temperature sensitivity, our phase-2 clock will employ a mixed N_2/Ar buffer gas. Since the temperature coefficients of N_2 and Ar have opposite signs **[12]**, an appropriate pressure of these two buffer gases should lead to a near zero temperature coefficient. Figure 3 shows the temperature-induced variation of the 0-0 hyperfine transition in our phase-2 clock, which has a resonance cell filled with 39 torr N_2 and 61 torr Ar.

Based on these data, and the fact that our phase-1 clock was operated at a resonance cell temperature of 47^{o}C, we see that, by using this mixed buffer-gas cell, our clock's temperature sensitivity will be about a factor of seven smaller. However, we should be able to do better than this if we operate our phase-2 clock at a temperature of 73.8^{o}C, where the clock frequency as a function of temperature has an extremum. Assuming that we can determine the extremum of our clock's temperature coefficient to ±0.1 ^{o}C, and that the short-term frequency stability is not negatively impacted by the higher operating temperature, Fig. 4 compares our potential phase-2 clock performance with our phase-1 clock performance.

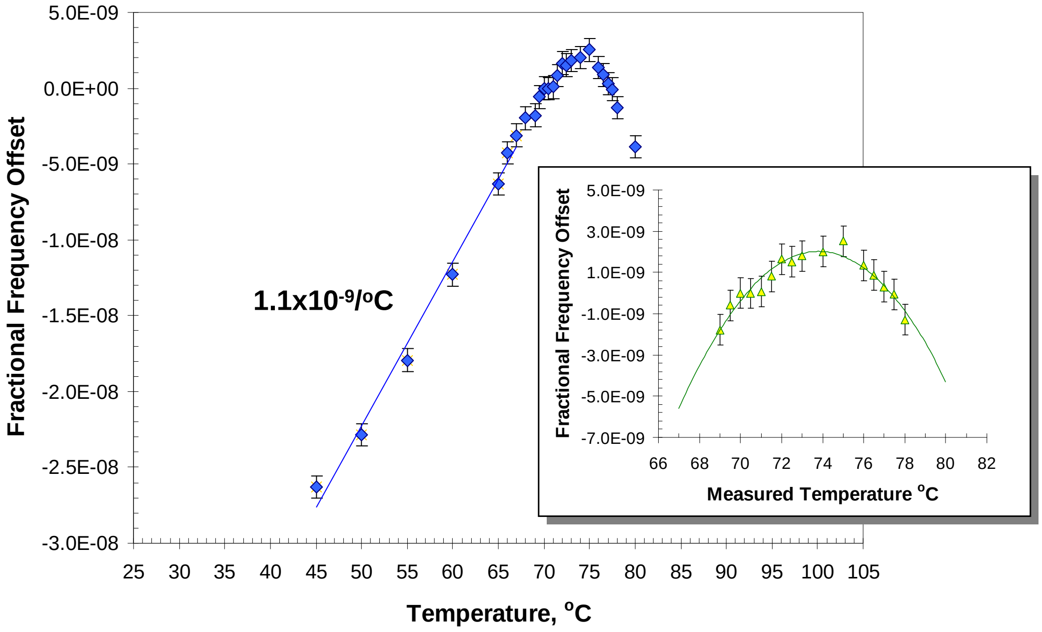

Figure 3. Fractional frequency shift of our phase-2 clock as a function of temperature. At our phase-1 clock's operating temperature of 47^{o}C, our phase-2 clock will have a factor of seven lower temperature sensitivity. However, operating the clock at 73.8^{o}C, we should be able to drive the temperature coefficient to near zero.

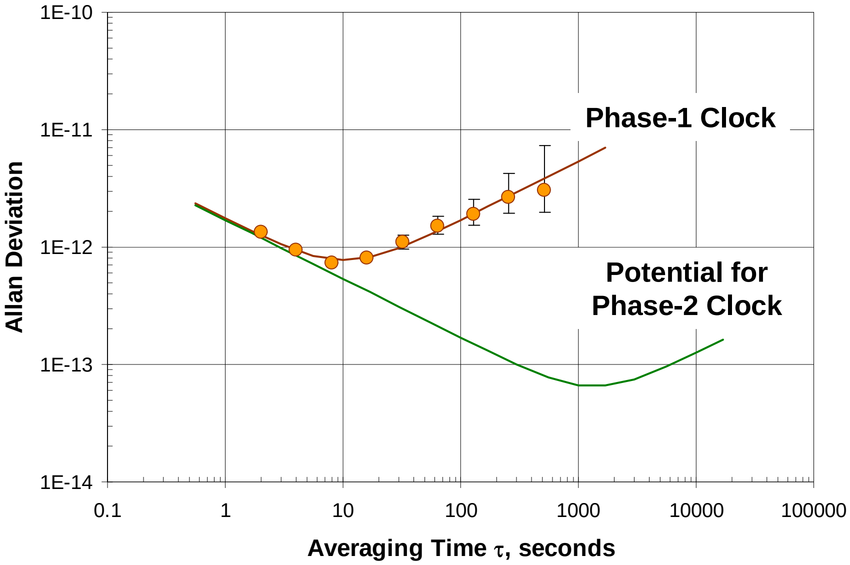

Figure 4. Potential performance of our phase-2 conventional laser-pumped Rb clock.

SUMMARY

In order to achieve shot-noise-limited performance in a conventional, laser-pumped vapor-cell atomic clock, it is necessary to mitigate PM-to-AM conversion noise. Our approach to this problem has been to increase the buffer-gas pressure in the resonance cell so that the atoms are unable to follow the laser's fluctuating phase. This approach, however, greatly increases the sensitivity of the clock to temperature variations. Here, we demonstrated that temperature fluctuations were indeed the origin of our phase-1 clock's long-term frequency instability. Our proposal to deal with this problem is to employ a mixed N_2/Ar buffer gas in the resonance cell, and to operate the resonance cell at an elevated temperature.

In addition to measuring our phase-2 clock's Allan deviation and demonstrating that this approach is a viable means of improving a laser-pumped vapor-cell clock's long-term stability, we also plan to investigate means of further improving the clock's short-term stability. We believe that our phase-1 clock's short-term performance may have been limited by a light-shift effect arising from our need to modulate the laser wavelength in order to lock the laser to the optical resonance. We anticipate that a proper choice of laser-wavelength modulation frequency and amplitude could reduce this light-shift effect.

ACKNOWLEDGMENT

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