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An Atomic Beam Velocity Servo for Optically Pumped Cesium Frequency Standards

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Abstract—**When evaluating the frequency uncertainty of a cesium-beam primary frequency standard, accurate measurement and control of the atomic velocity distribution is important. In frequency standards which employ atoms with thermal velocities, the measured atomic resonance frequency differs from the true resonance by several parts in 10^{13} due to the second-order Doppler shift. To achieve a frequency uncertainty for NIST-7 of 5 parts in 10^{15}, the uncertainty introduced by the second-order Doppler shift must be no more than one part in 10^{15}. In addition, the Doppler shift must remain constant throughout the measurement of the atomic resonance frequency. We have developed a new optical technique for efficiently measuring the atomic velocity in real-time. This technique is compatible with the slow square-wave digital frequency servo used by the U.S. primary frequency standard NIST-7.**

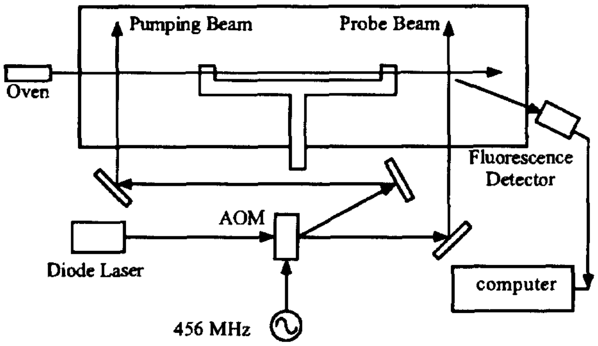

Fig. 1. Schematic of NIST-7. AOM: acousto-optic modulator. For clarity, the microwave synthesis chain has been omitted.

I. Introduction

We have previously developed two independent techniques for measuring the velocity distribution of atoms in a cesium-beam frequency standard: Ramsey fringe inversion[1], and gated optical pumping.[2] While these techniques produce accurate results, they are too slow for use in real-time monitoring and control of the atomic beam. Recent improvements in the line-shape inversion method[3] have reduced our uncertainty in the second-order Doppler shift to $1 \cdot 10^{-15}$. This improvement places an even greater burden on the stability of the atomic beam: the frequency shift must be stable at or below a level of $1 \cdot 10^{-15}$ for the duration of a frequency measurement.

II. Review of Optical Pumping and Detection of Atoms

Figure 1 is a schematic diagram of NIST-7, an optically pumped cesium-beam primary frequency standard. The oven produces a continuous supply of cesium atoms that are uniformly distributed between the two hyperfine levels of the ground-state ($F = 3, 4$ in figure 2). This population symmetry is removed using lasers. Two laser beams are generated from a single diode laser by an acousto-optic modulator (AOM). The atoms pass through a "pumping beam" that is tuned to the optical transition $F = 4 \rightarrow F' = 3$. This diffracted beam is produced by driving the AOM at 456 MHz. The atoms absorb this energy and are transferred to the $F' = 3$ excited state. This state has a short lifetime. The atoms emit a photon and return to one of the ground-state levels. Those that fall to the $F = 3$ level remain there, because the laser does not excite this resonance. Those that fall to the $F = 4$ level repeat this process until they are transferred to the $F = 3$ level. This process, called optical pumping, shuttles virtually all of the atoms into the $F = 3$ level of the ground state.

Lasers are also used to detect the atoms. At the far end of the beam, the atoms pass through another laser beam. This laser is tuned to the optical transition $F = 4 \rightarrow F' = 5$. Atoms in the $F = 4$ state absorb this energy and are transferred to a higher energy

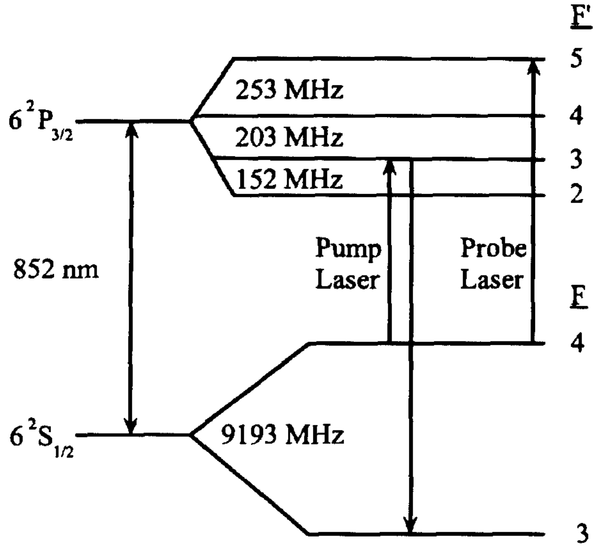

Fig. 2. Cesium Energy Level Diagram.

state ($F' = 5$). When they decay, a photon is emitted. These photons are collected with mirrors and detected by a silicon photodiode. Atoms in the $F' = 5$ level can only decay back to where they started, the $F = 4$ level. Therefore, this process may be repeated numerous times, producing many photons for each atom.

Under normal operation, optical pumping and detection are used in conjunction with Ramsey's method of separated oscillatory fields to measure the cesium hyperfine transition. However, the optical geometry of NIST-7 can also be exploited to obtain real-time information about the atomic beam velocity. This information can then be used to stabilize the second-order Doppler shift using a feedback control system.

III. MODULATED OPTICAL PUMPING

We have developed a technique that permits real-time monitoring and servo control of the atomic velocity using modulated optical pumping. Figure 3 is a schematic diagram of the apparatus. The pump laser intensity was reduced below the level required for complete optical pumping, allowing some atoms to remain in the $F = 4$ ground state. Information was then "written" on the atomic beam by amplitude modulating the pump laser with an acousto-optic modulator. The signal was encoded on the atomic beam through the number of unpumped atoms remaining in the $F = 4$ state. This signal was carried by the atoms down the beam-tube and recovered using another laser beam. An independent, continuous-wave (CW) diode laser[4] was tuned to the detection transition $F = 4 \rightarrow F' = 5$. The resulting fluorescence was collected and converted to a photocurrent which was proportional to the number of atoms in the $F = 4$ state.

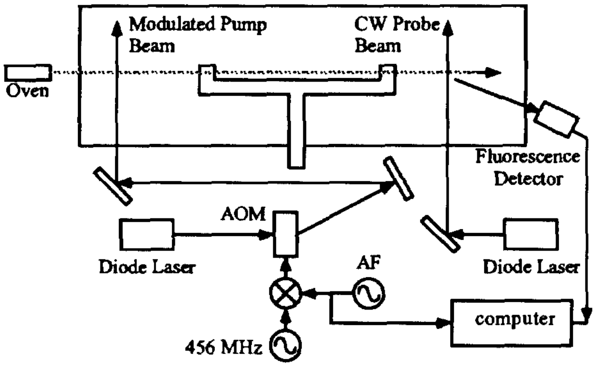

Fig. 3. Experimental Setup for Modulated Optical Pumping. AOM: acousto-optic modulator. AF: Audio-frequency oscillator. No microwave excitation is used in the measurement of the transfer function.

We can view the atomic beam as a cesium transmission line. Like any transmission medium, the atomic beam has a transfer function. It was measured in the absence of any microwave excitation by amplitude modulating the optical pumping beam with an audio-frequency (AF) waveform. The transfer function was then obtained from the ratio of the Fourier transform of the response to that of the excitation as a function of frequency. The upper trace of figure 4 is a plot of the phase response as a function of excitation frequency. This measurement was performed for two different temperatures of the cesium oven. The two corresponding phase responses were subtracted and the phase change is shown in the lower trace of figure 4. These data indicate that the phase delay at a specific excitation frequency can be used as a measure of the beam velocity. To illustrate the improved sensitivity of this method to changes in the beam velocity, it was compared to the gated optical pumping technique. The lower trace of figure 5 is a plot of the phase response of the cesium beam (for 70 Hz square-wave excitation) vs. oven temperature. For comparison, the upper trace is a plot of the atomic beam's mean transit time across the Ramsey cavity, measured by the gated optical pumping method. The phase response method yields a better signal to noise ratio than does gated optical pumping, despite the fact that the phase response measurements are performed in just 1 second. The gated optical pumping data take 360 seconds per point. This improvement is due to more efficient use of the atoms. Gated optical pumping produces a short burst (500 microseconds) of atoms whose time of flight

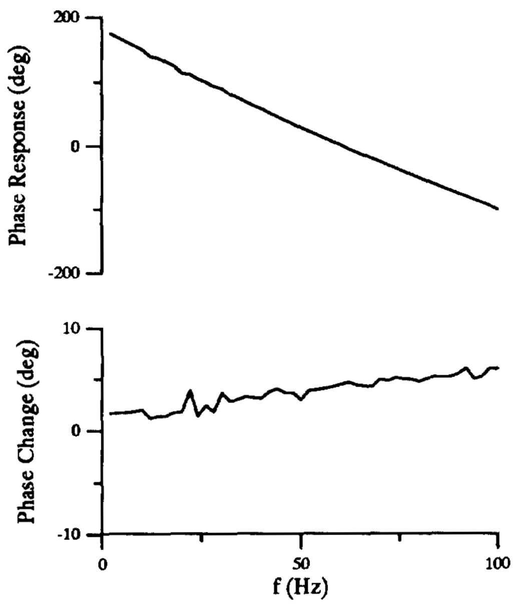

Fig. 4. Phase Response of the Atomic Beam.
Upper trace: Atomic beam phase response. Lower trace: Change in phase response for a change in oven temperature of $\Delta T = 11$ K.

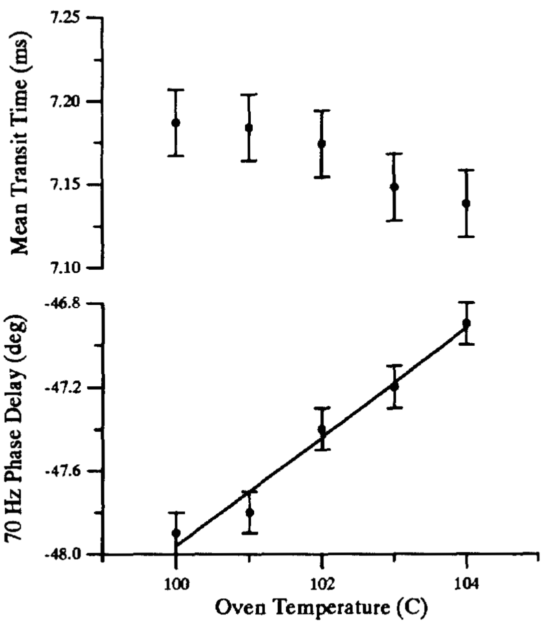

Fig. 5. Mean Transit Time and Phase Response
Upper trace: mean atomic beam transit time vs. oven temperature. Lower trace: phase response vs. oven temperature. The solid line has a slope of 0.3 deg/K. The error bars are $\pm 1\sigma$.

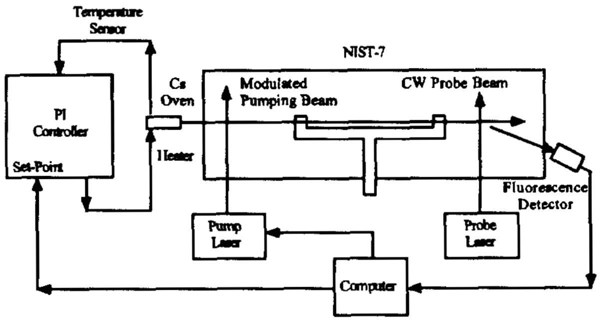

Fig. 6. Atomic Beam Velocity Servo
The temperature set-point of a proportional-integral controller is adjusted to stabilize the phase response and therefore the beam velocity.

across the beam-tube reflects the velocity distribution. Since very few atoms ($\approx 500,000$) contribute to each pulse, thousands of pulses must be averaged to achieve a high signal to noise ratio. The gated optical pumping method has a duty cycle of only 1 percent. The phase response method has a duty cycle of 50 percent. Half of the atoms contribute to the signal.

IV. ATOMIC BEAM VELOCITY SERVO

Figure 6 is a schematic diagram of a velocity servo that uses the atomic beam phase response as an error signal. The microwave interrogation signal is turned off momentarily as the phase response is measured at 70 Hz. Deviations of the phase from an initial phase set-point serve as a velocity error signal. A computer then steers the set-point of a proportional-integral temperature controller on the cesium oven in order to minimize this error signal. The performance of this servo was evaluated by monitoring the atomic beam's mean transit time by an independent method: gated optical pumping. Figure 7 is a plot of the Allan deviation of the mean transit time as a function of the averaging time τ. The right vertical axis indicates the contribution of the mean transit time to fluctuations in the clock frequency through the second-order Doppler shift. The Allan deviation decreases at a rate consistent with white noise fluctuations to a level of $5 \cdot 10^{-16}$ for $\tau = 7000$ seconds. This level is well below our goal of a fractional frequency uncertainty of $1 \cdot 10^{-15}$.

V. CONCLUSION

Improvements in the measurement of the second-order Doppler shift place tight constraints on the stability of the atomic beam velocity. We have developed a feedback control system using information from the atoms to stabilize the shift at several parts in 10^{16} for

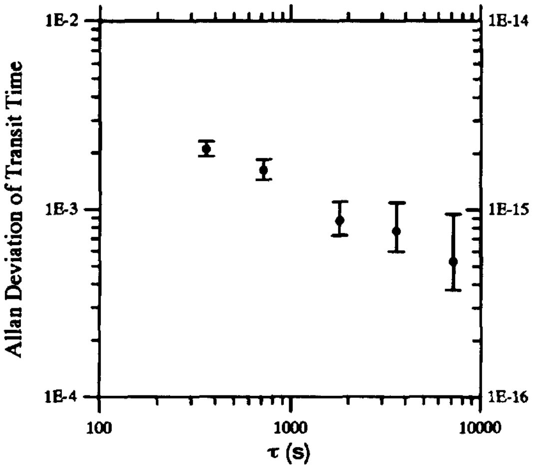

Fig. 7. Performance of the Velocity Servo
This is a plot of the Allan deviation of the mean transit time and its contribution to the clock frequency through the second-order Doppler shift.

the duration of our frequency measurements.

REFERENCES

[1] J. H. Shirley, "Velocity Distributions From the Fourier Transforms of Ramsey Lineshapes," in *Proc. 43rd Ann. Symp. on Freq. Control*, 1989, pp. 162-167.

[2] W. D. Lee, J. H. Shirley, and R. E. Drullinger, "Velocity Distributions of Atomic Beams by Gated Optical Pumping," in *Proc. 1994 IEEE Int. Freq. Control Symp.*, 1994, pp. 658-661.

[3] J. H. Shirley "Velocity Distributions from the Fourier Transforms of Ramsey Line Shapes," in *Proc. 1996 Conf. on Prec. Electromagnetic Meas.*, 1996.

[4] D. A. Jennings, W. D. Lee, R. E. Drullinger, and J. M. Lopez-Romero, "DBR Laser Diodes for Optically Pumped Cs Frequency Standards," in *Proc. 1996 Conf. on Prec. Electromagnetic Meas.*, 1996.