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Velocity Distributions of Atomic Beams by Gated Optical Pumping

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Abstract— In evaluating the accuracy of a cesium-beam frequency standard, accurate measurement 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 the frequency accuracy goal for NIST-7 of $1 \cdot 10^{-14}$, the uncertainty in the second-order Doppler shift must be no more than a few parts in 10^{15}. This requirement establishes an upper bound on the uncertainty of the mean-square atomic velocity of about 1 percent. We present the results of experiments designed to measure the velocity distribution of NIST-7 using two independent techniques: gated optical pumping, and Ramsey fringe inversion. We show that these techniques yield velocity distributions and corresponding second-order Doppler shifts that agree within the stated tolerances.

I. INTRODUCTION

A variety of techniques have already been developed to measure the velocity distribution of atomic beams in atomic frequency standards. Boulanger's method[1] is based upon the measurement of the amplitude of the central maximum of the Ramsey resonance as a function of the microwave power level. This technique is probably not appropriate for NIST-7. At the present static magnetic field (C-field) magnitude, the peak amplitude of the Ramsey fringe does not settle to a constant value (as microwave power is increased) before adjacent transitions begin to interfere with the measurement. A novel method introduced by Hellwig[2] yielded velocity selection of the atomic beam by application of short microwave pulses whose widths were equal to the transit time of a given velocity group through one end of the Ramsey cavity. The pulse separation was the transit time across the entire cavity. This technique is, however, ineffective for evaluating the velocity distribution of NIST-7. The "mono-velocity" Ramsey lineshapes obtained using this technique are contaminated by Ramsey fringes from harmonics of the velocity group being studied. This effect is quite pronounced in NIST-7 which exhibits a full Maxwellian velocity distribution. Jarvis[3] introduced a technique whereby the velocity distribution was obtained from Fourier transforms of the Ramsey lineshape at each of several known microwave power levels. We have modified and extended this technique[4] to serve as our primary tool for measuring velocity distributions. However, for a thorough evaluation of the frequency accuracy of NIST-7, we desire two independent measurement techniques to estimate the major frequency biases present. Thus, we have developed the additional technique of gated optical pumping.

II. EXPERIMENTAL METHOD

The unique design of the NIST-7 primary frequency standard, specifically the optical pumping scheme,[5] is well suited for this measurement technique. Figure 1 is a schematic of NIST-7.

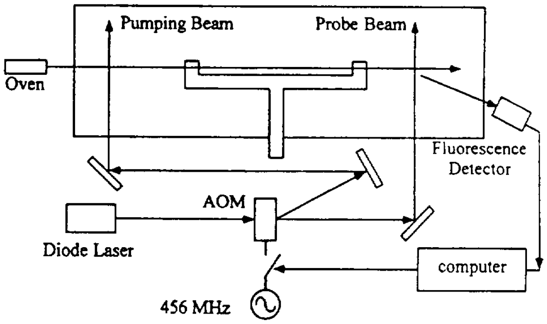

Fig. 1. Schematic of NIST-7.

The oven emits a collimated beam of cesium atoms which are uniformly distributed among the $F = 3$ and $F = 4$ ground states. (See figure 2).

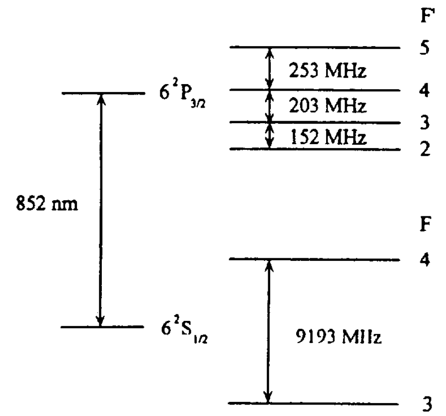

Fig. 2. Cs Energy Level Diagram.

In the optical pumping region virtually all of the atoms are pumped into the $F = 3$ ground state by a laser which is tuned to the optical transition $F = 4 \rightarrow F' = 3$. The atoms then traverse the Ramsey cavity and those that undergo a transition to the $F = 4$ ground state are detected by a probe laser which is tuned to the optical cycling transition $F = 4 \rightarrow F' = 5$. The resulting fluorescence is collected and detected by a photodiode.

Both the optical pumping and probe laser beams are derived from a single external-cavity $Al_xGa_{1-x}As/GaAs$ diode laser. The laser is frequency locked to the $F = 4 \rightarrow F' = 5$ cycling transition using saturation spectroscopy in a cesium vapor cell. The output passes through an acousto-optic modulator (AOM) where the undiffracted beam serves as the probe beam. When RF power is applied to the AOM a diffracted beam is generated that is shifted down in frequency by an amount equal to the frequency separation of the $F' = 3$ and $F' = 5$ levels in the excited state. This beam serves as the optical pumping beam.

To implement the gated optical pumping method, no microwave field is applied to the cavity; the time-of-flight distribution is recorded using lasers only. In steady-state, when the optical pumping beam is on, virtually all of the atoms are pumped into the $F = 3$ hyperfine level. Since no microwave transitions take place, there exists no significant fluorescence signal from the probe region. The atomic transit-time distribution is measured by switching off the optical pumping beam for a time interval τ using the computer-controlled RF switch connected to the AOM. During this time interval, a small group of atoms (uniformly distributed among the $F = 3$ and $F = 4$ hyperfine levels) are allowed to transit the optical pumping region unpumped. When the optical pumping beam is switched back on, subsequent atoms are transferred to the lower ground state. This short burst of unpumped atoms spreads spatially as it propagates down the beam tube due to the distribution of atomic velocities. These atoms then arrive at the detection beam at times determined by their velocities. The resulting fluorescence-pulse represents the atomic transit-time distribution.

We adjust τ so that the slowest atoms of interest have sufficient time to traverse the optical pumping region. This sets a lower limit on τ. Increasing τ also increases the number of atoms contributing to the measurement; thus the signal to noise ratio improves. However, large values of τ reduce the resolution of the transit-time measurement.

The output of the photodiode amplifier represents the fluorescence-pulse convolved with the impulse response of the photodiode and its associated amplifier. To recover the shape of the fluorescence-pulse, the effects of the photodetector's transfer function must be removed. Figure 3 shows the measured frequency response of the photodetection system.

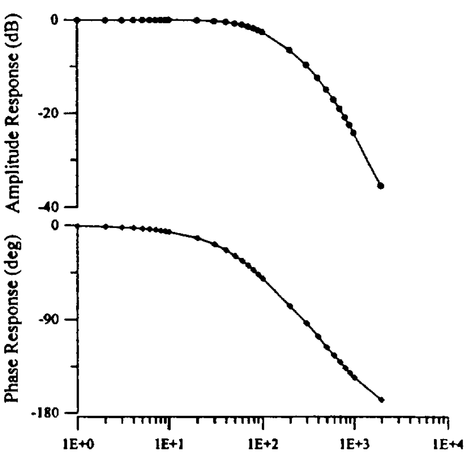

Fig. 3. Frequency Response of the Photodetection System.

The transfer function was determined by measuring the amplitude and phase response of the photodetection system to a sinusoidal optical excitation. The cutoff frequency of ≈ 100 Hz is largely determined by the 10 GΩ feedback resistance used in the photodetector's transimpedance amplifier. The spectrum of the photoelectric pulse was corrected for the nonuniform amplitude and phase delay characteristics of the photodetector and its amplifier. Figure 4 shows a photoelectric pulse before and after this deconvolution operation was performed.

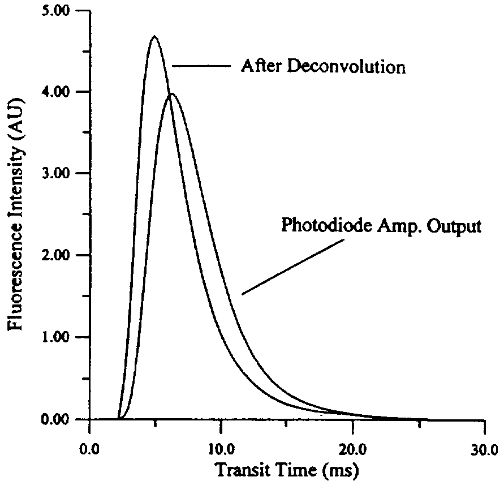

Fig. 4. Raw and Deconvolved Photoelectric Pulses. τ = 500 microseconds. 4000 pulses were averaged for this measurement.

The rise time of the pulse has been shortened significantly with the restoration of the high frequency components of the pulse. The time axis of this figure has been normalized so that after deconvolution this pulse represents the distribution of atomic transit-times across the Ramsey cavity, rather than from pump-laser to probe-laser. The velocity distribution $\sigma(v)$ is obtained from the transit-time distribution $\rho(T)$ by the relation

$$\sigma(v) = (L/v^2)\rho(L/v), \qquad (1)$$

where v is the atomic velocity and L is the length of the Ramsey cavity. The corresponding second-order Doppler correction for this distribution under normal operating conditions is $-3.60 \cdot 10^{-13}$.

Atomic transit-time distributions from the gated optical pumping technique were compared to those obtained using a Ramsey fringe inversion method.[4] This method is optimized for use with long laboratory standards where the excitation length is much less than the drift region length. The transit-time distribution is obtained from a set of Ramsey lineshapes recorded at various microwave power levels. This data is collected using the digital servo of figure 5.

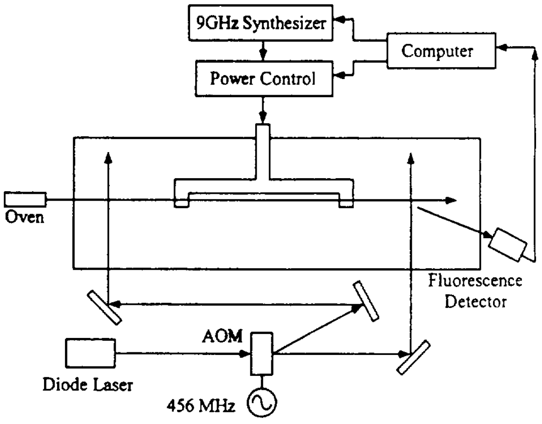

Fig. 5. Schematic Diagram of the Digital Servo.

A computer controls both the microwave frequency and power level while monitoring the beam fluorescence from the probe region. A computer program then sweeps the microwave frequency and records the Ramsey lineshape, incrementing the microwave power between sweeps. Figure 6 shows a typical set of Ramsey lineshapes.

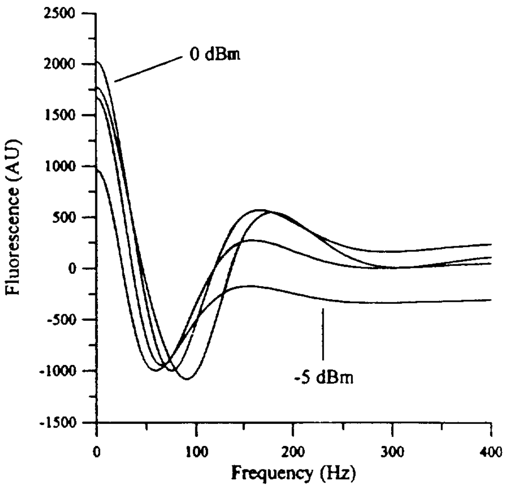

Fig. 6. Ramsey Lineshapes as a Function of Microwave Power.

The corresponding transit-time distribution is shown in figure 7.

The second-order Doppler correction for this distribution under normal operating conditions is $-3.58 \cdot 10^{-13}$, in excellent agreement with the results obtained from gated optical pumping.

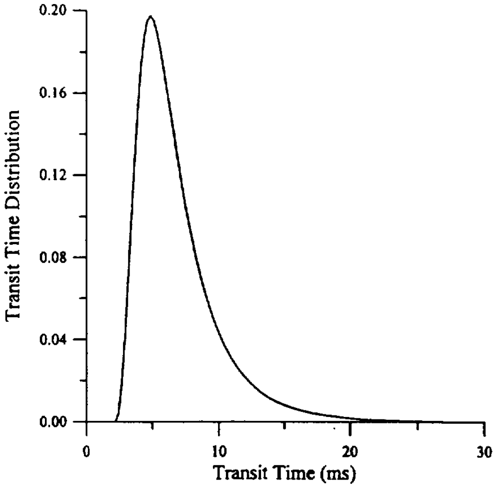

Fig. 7. Transit-time Distribution from Ramsey Fringe Inversion.

III. Conclusion

During the evaluation of the frequency accuracy of NIST-7, we desire two or more independent techniques for estimating the major frequency biases present in the standard. We have developed two techniques for measuring the velocity distribution, required for computing the second-order Doppler correction: gated optical pumping and Ramsey fringe inversion. These two techniques yield velocity distributions in excellent agreement. The second-order Doppler correction was computed for several microwave power levels using transit-time distributions obtained from the two methods. While the corrections varied by nearly 2 parts in 10^{13} over a 7.5 dB microwave power range, the computed corrections from the two techniques differed by no more than $2 \cdot 10^{-15}$.

References

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