

PRELIMINARY INVESTIGATIONS WITH THE NIST OPTICALLY PUMPED  
PRIMARY FREQUENCY STANDARD

R. E. Drullinger, J. H. Shirley, D. J. Glaze, John Lowe, HoSeong Lee\* and A. S. Zil'rov†  
National Institute of Standards and Technology,  
Boulder Colorado, 80303 USA

**Abstract**

An optically pumped, cesium beam, primary frequency standard has been constructed at NIST. The atomic beam tube is essentially complete but the lasers and electronics remain areas of active research. We have used the system to demonstrate a solution to the problem of coherence trapping of population that could otherwise limit clock performance. We also report spectra taken on the system and draw conclusions about the beam tube construction and operation.

**The Apparatus**

An optically pumped, cesium beam, primary frequency standard has been constructed at NIST and is undergoing preliminary testing. The design goal is to have a nearly self evaluating, continuously operating clock with a short term stability characterized by  $\sigma_y(\tau) \approx 4 \times 10^{-13} / \sqrt{\tau}$  and an overall accuracy of about one part in  $10^{14}$ . The analysis of systematic errors and the resulting logic that led to the design of the atomic beam tube have been published previously[1]. The geometric features of the design are shown in Fig. 1 where only half of the tube is shown because of symmetry. The microwave cavity is about 155 cm long and is terminated with ends designed to minimize distributed-cavity, phase shift[2]. There are separate regions of optical state preparation and detection at each end of the system to allow for simultaneous counter-propagating atomic beams[3]. The C-field is axial and is generated by a solenoid which extends over the entire length of the standard. The atomic beam cross section is defined by the windows in the microwave cavity to be 3 mm in diameter.

Newly developed electronics have been built and are being tested. A new modulator scheme is described in these proceedings[4].

Two laser systems were assembled for these experiments. They were external cavity, grating feedback systems made after the style of reference 5 but using commercially available diodes. They were individually referenced to saturated absorption features generated in room temperature cells using a Doppler compensated probe scheme[6]. For the experiments reported here, only one laser was used to prepare the atoms by pumping on the  $F=4 \rightarrow F'=4$  transition. The light beam for optical detection was synthesized from the pump laser with an acousto-optic modulator to drive the  $F=4 \rightarrow F'=5$  transition.

Contribution of the U.S. Government, not subject to copyright.  
\* permanent address: Korea Standards Research Institute, Time and Frequency Laboratory, P.O.Box 3, Taedok Science Town, Taejon 305-606, Korea

† permanent address: P.N.Lebedev Physics Institute, Academy of Sciences of the USSR, Leninsky prospect 53, Moscow 117924, USSR

PRINCIPAL COMPONENTS OF NIST-7

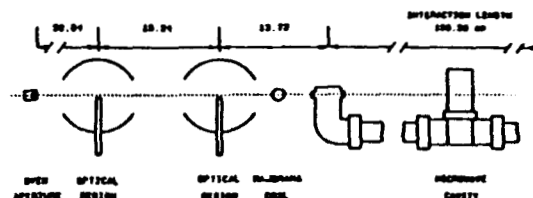


Fig. 1. Schematic representation of the atomic beam tube for NIST-7

The linewidth and frequency stability of the lasers were demonstrated with the following experiments. Both lasers were aligned in the state preparation region as for two-laser optical pumping[7]. One laser was locked to the  $F=4 \rightarrow F'=4$  transition and the other scanned across the  $F=3 \rightarrow F'=4$  transition. The dark resonances[8] were easily observed with about 25% contrast. Correspondingly, with one laser locked to the  $F=4 \rightarrow F'=4$  transition and the other locked to the  $F=3 \rightarrow F'=4$ , the lasers were heterodyned together on a fast photodiode and the beat note recorded on a spectrum analyzer. The average of 500 sweeps is shown in Fig. 2. The frequency modulation necessary for the lock to the atoms was suppress in the beat note by synchronizing the modulation on the two lasers. The 3 dB width of the beat is about 500 kHz.

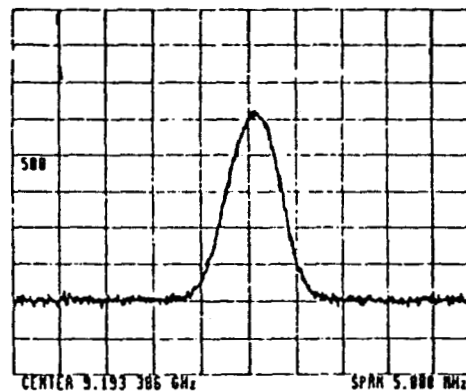


Fig. 2. Beat note between two lasers individually locked to saturated absorption features in cesium cell. One laser is locked to the  $F=4 \rightarrow F'=4$  transition, while the other is locked to the  $F=3 \rightarrow F'=4$  transition.

## Coherence Trapping

When optical state preparation is attempted at low magnetic fields, coherent trapping of the population (nonlinear Hanle effect) may occur[9], leading to incomplete pumping. When linearly  $\sigma$  polarized light is used to excite a transition for which  $F' \leq F$ , there is a linear combination of Zeeman sublevels which is not coupled to the optical field. Such a state cannot be pumped and the population remains trapped. In a magnetic field, Larmor precession causes the trapped state to evolve into a different linear combination of Zeeman sublevels which is coupled to the optical field and hence can be pumped. By using a sufficiently high magnetic field in the pumping region, trapping can be avoided[10]. It is, however, still possible to achieve complete optical pumping in a low magnetic field in the following way:

If a linear polarization intermediate between  $\sigma$  and  $\pi$  is used, there will again be some linear combination state that is not coupled to the field. However, the exact combination depends on the direction of the polarization. Hence, by changing the polarization direction back and forth, atoms that are at first trapped in one polarization will be pumped by the second polarization while atoms trapped by the second polarization will be pumped by the first. For complete pumping the polarization must be changed several times during the transit time of the atoms across the pumping region. One can change the polarization either in time, as with an electro-optic modulator, or in space, as in polarization gradient cooling[11]. This latter scheme involves retro-reflecting the optical pumping beam back through the pumping region with a quarter-wave plate in front of the mirror.

Figure 3 shows a typical scan of the fluorescence yield from the optical pumping region as a function of magnetic field. Curve a shows the effect of coherence trapping where some of the population is not optically pumped at low magnetic field. Curve b shows the much greater degree of optical pumping achieved when the polarization gradient scheme is used.

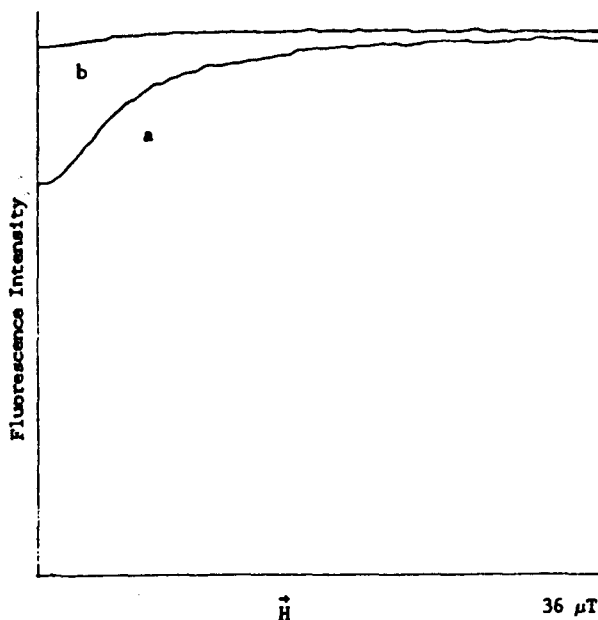


Fig. 3. Fluorescence from the optical pumping region as a function of magnetic field. The transition is the  $F=3 \rightarrow F'=3$ . Trace a is with linear  $\sigma$  polarization while trace b is made with counter-propagating, orthogonally polarized beams.

## Spectra

To begin characterizing the performance of the atomic beam tube, we have recorded a number of spectra of the cesium hyperfine transition. Some of these are reproduced here as figures 4-6. The spectra were taken under the following conditions: The temperature of the oven was  $90^\circ\text{C}$ . The detection laser beam was about 4 mm in diameter, with a power of  $35 \mu\text{W}$  and tuned to the  $F=4 \rightarrow F'=5$  transition. This resulted in an average of about 20 scattered photons per atom in the  $F=4$  state and essentially unit detection probability. The pump laser was tuned to the  $F=4 \rightarrow F'=4$  level and had about  $300 \mu\text{W}$  in a 4 mm diameter beam. Its polarization was established by the use of the polarization gradient pumping scheme outlined above.

Figure 4 shows the hyperfine spectrum excited by a microwave power a few decibels below optimum. It consists of the 7 expected  $\Delta m=0$  Zeeman components, each of which has a Ramsey interference pattern superimposed on a Rabi pedestal. The symmetry resulting from the optical state preparation is apparent. The symmetry of the Ramsey peaks on the high-field Rabi peaks demonstrates the C-field uniformity expected from the long solenoid. The axial-field geometry chosen for this standard gives rise to a microwave field distribution that varies as a half sine wave in the direction of the atomic beam. The resulting Rabi line shape with narrow, smooth tails can be seen at each end of the spectrum. The spectral symmetry and line shapes should result in no Rabi[12] or Ramsey[13] pulling at the design accuracy.

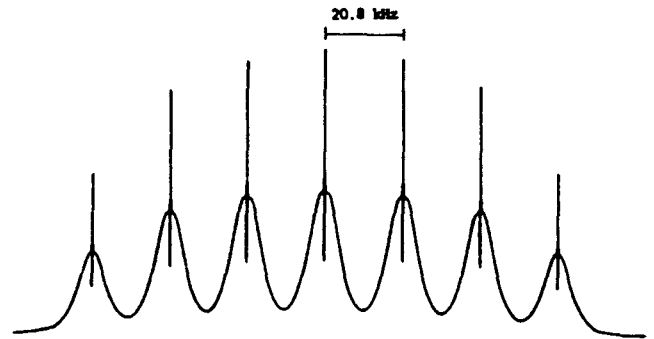


Fig. 4. The entire hyperfine spectrum showing all 7  $\Delta m=0$  Zeeman components. The microwave power is a few decibels below optimum.

With the microwave radiation tuned well off resonance or turned off, blocking the atomic beam gives a measure of the degree of optical pumping. Using the central peak as a calibrator, we can show that the amount of population left in the  $F=4$  state after optical state preparation is less than 0.1% of the total population. Correspondingly, blocking the detector laser demonstrates that the scattered light background is on the order of 5% of the signal level in the main peak.

Figure 5 shows an expansion of the central Ramsey peak. The linewidth is 65 Hz ( $Q = 1.4 \times 10^6$ ), in agreement with theoretical predictions based on the geometry of the standard, the oven temperature, and the chosen preparation and detection schemes. The signal-to-noise ratio at line center is 5000 in a 1 Hz bandwidth centered at 49 Hz. This is a factor of 3 smaller than the theoretical limit for these conditions and is a result of the beam signal at the detector being below its design value. The reason for this loss of signal is not known at this time.

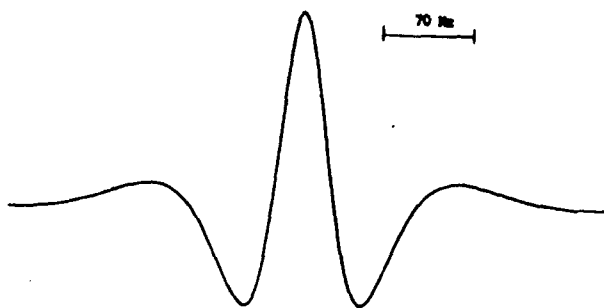


Fig. 5. Central Ramsey feature, "clock transition." The linewidth is 65 Hz and the S/N is 5000 in a 1 Hz bandwidth at 49 Hz.

Figure 6 shows the  $m_F = -3 \rightarrow m_F = -3$  transition at a higher C-field value and a microwave power about 4 dB above optimum. It shows in greater detail the quality of the C-field by the perfect symmetry of the Ramsey peak on the Rabi peak. It also shows the presence of  $\Delta m = \pm 1$  transitions. If we scale the size of these peaks for the change in power to optimum power and for the change in transition probability for those peaks next to the "clock" transition, the ratio of the main peak to the  $\Delta m = \pm 1$  peaks adjacent to the main peak becomes 400:1. In this standard, these transitions should be excited only by curvature in the microwave field at the edges of the atomic beam. Calculating the effect of this field curvature over the atomic beam window results in a mean square value for the RF field perpendicular to the C-field which is 1/100th of the mean square field parallel to the C-field. The field curvature is thus adequate to explain the observed level of  $\Delta m = \pm 1$  transitions. A quantitative theory for the  $\Delta m = \pm 1$  lineshapes, which are excited by a "half cosine wave" is required to get quantitative agreement.

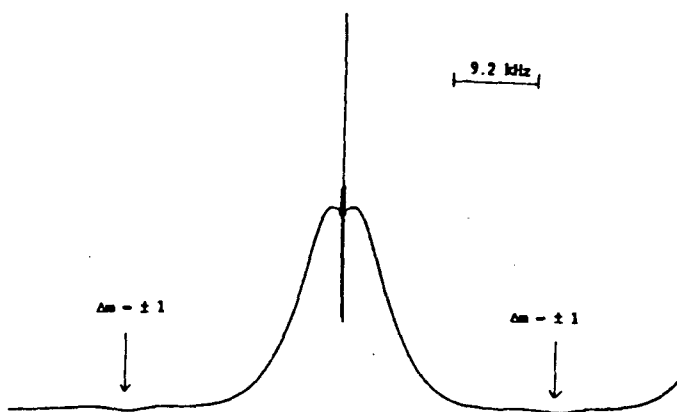


Fig. 6. The  $m_F = -3 \rightarrow m_F = -3$  transition at 4 dB above optimum power showing the  $\Delta m = \pm 1$  transitions.

### Conclusions

Preliminary experiments have been performed with the NIST optically pumped, primary frequency standard. A polarization gradient scheme of optical pumping has been demonstrated to result in complete optical pumping even at low magnetic fields where coherence trapping could have been a

problem. Microwave spectra have been used to evaluate some aspects of the standard. The "clock" signal line Q is the expected value of  $1.4 \times 10^6$ . The signal-to-noise ratio on the "clock" transition is essentially atomic shot-noise limited at about 5000 (in a 1 Hz bandwidth at 49 Hz) in the present experiments. The spectral symmetry indicates that magnetic field homogeneity and spectral pulling will not be important at the design accuracy. Finally, the scattered light does not degrade the signal-to-noise ratio.

**Acknowledgements** One of the authors, RED, would like to express his gratitude to SungHoon Yang for enjoyable and valuable interactions during these experiments.

### References

- 1) Robert E. Drullinger, David J. Glaze, J. L. Lowe and Jon H. Shirley, *IEEE Trans. Instrum. Meas.* **IM-40**, (1991).
- 2) Andrea DeMarchi, Jon Shirley, David J. Glaze and Robert Drullinger, *IEEE Trans. Instrum. Meas.* **IM-37**, 185 (1988).
- 3) R. E. Drullinger, in *Proc. 44th Annual Symposium on Frequency Control*, 76 (1990).
- 4) John Lowe and F. L. Walls, "Ultralinear Small-Angle Phase Modulator," these proceedings.
- 5) A. M. Akul'shin, V. L. Velichanskii, A. S. Zibrov, V. V. Nikitin, V. A. Sautenkov, and G. G. Kharisov, *Sov. J. Quantum Electron.* **18**, 1214 (1988).
- 6) T. W. Hänsch, I. S. Shahin and A. L. Shawlow, *Phys. Rev. Lett.* **27**, 707 (1971).
- 7) L. S. Cutler, U.S. Patent No. 4,425,653.
- 8) G. Orriols, *Nuovo Cimento* **55b**, 1 (1979).
- 9) G. Théobald, N. Dimarcq, V. Giordano and P. Cézé, *Opt. Commun.* **21**, 256 (1989).
- 10) V. Giordano, A. Hamel, P. Petit, G. Théobald, N. Dimarcq, P. Cézé and C. Audoin, "New Design for a High Performance Optically Pumped Cesium Beam Tube," to be published.
- 11) J. Dalibard and C. Cohen-Tannoudji, *J. Opt. Soc. Amer. B*, **11** 2023 (1989).
- 12) A. DeMarchi, G. D. Rovera and A. Premoli, *Metrologia* **20**, 37 (1984).
- 13) L. S. Cutler, C. A. Flory, R. P. Giffard and A. DeMarchi, "Frequency pulling by hyperfine  $\sigma$ -transitions in Cesium beam atomic frequency standards," *J. Appl. Phys.* March 1, (1991).