OPTICALLY PUMPED SMALL CESIUM BEAM STANDARDS; A STATUS REPORT*

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Abstract

We report on our project to study and to demonstrate the potential performance achievable in cesium beam frequency standards in which laser driven optical pumping is used for the atomic state selection and state detection in place of the conventional magnetic state selection. The beam tubes used have been derived from commercial devices. In the first unit the only functional change was a simple replacement of state selection magnets with optics. In a second unit, the magnetic shields and c-field have been extended to include the regions of optical pumping.

The short Ramsey cavities resulted in observed resonances which are 1300 Hz wide in agreement with theory for the geometry and detecting transition used. Both devices have demonstrated $\sigma_y(\tau) \leq 10^{-11}\ \tau^{-1/2}$ and are not yet limited by beam shot noise. Systematic errors resulting from resonantly scattered light have been shown to be less than 10^{-12} and one of these devices has been operated as a clock for 45 days.

Introduction

Optical Pumping in Cesium

The possibility of improving the performance of atomic beam frequency standards through the use of state selection and detection by optical means has been a subject of investigation for several years. [1-3] In recent times semiconductor laser diodes which are suitable for laboratory experiments in optical pumping have become commercially available. [4] These lasers operate with sufficient output power in a nearly single longitudinal mode, and sufficiently small intensity and frequency noise to allow some interesting measurements of optically pumped frequency standards. In addition, since the lasers can produce light at 852 nm, they can be used with the D2 transition in atomic cesium. The small size and low cost of laser diodes may allow the production of commercial cesium standards [5] with improved stability characteristics over present designs, or the construction of a laboratory primary frequency standard [6] with greater accuracy than that of existing primary cesium standards.

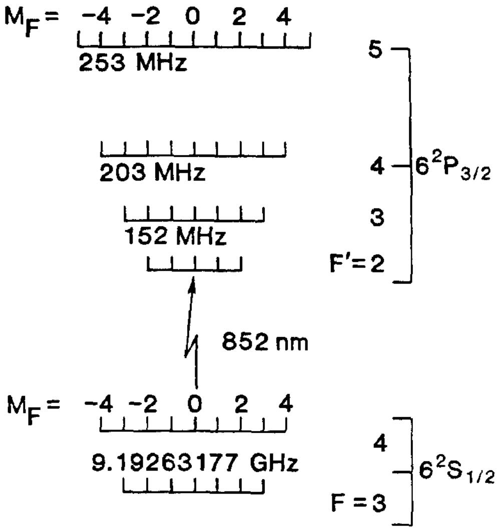

Figure 1. Energy level diagram for cesium optical pumping.

The energy level diagram of Figure 1 shows the relevant optical and microwave transitions for optical pumping in cesium. A number of different pumping schemes are possible, which may prepare cesium atoms in either the $^2S_{1/2}$, F=3 or F=4 hyperfine states. For example, the method used most often in the measurements reported here tuned a laser diode to the ($^2S_{1/2}$, F=4) $\leftrightarrow$ ($^2P_{3/2}$, F'=4) transition (852 nm) from the ground state to the second excited state. In this case the excited atoms decay back to both the F=3 and F=4 ground state levels with roughly equal probability. Continued exposure to the laser light drives the optical transition from the F=4 ground state again until no atoms are left in this state. The result is an increase in the population difference between the $^2S_{1/2}|F,m_F\rangle = |4,0\rangle$ and $|3,0\rangle$ magnetic sublevels. Figure 2 is a schematic representation of this optical pumping method, where Laser 1

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is the pump laser. Virtually complete optical pumping of the cesium occurs, with 95 to 99% of the cesium atoms placed into the F=3 ground state. This results in approximately 22% of the atoms in the $|F,m_F\rangle = |3,0\rangle$ state, as opposed to about 7% for traditional magnetic state selection. In addition, all velocity classes are included, instead of the 8 to 10% common for magnetic state selection.

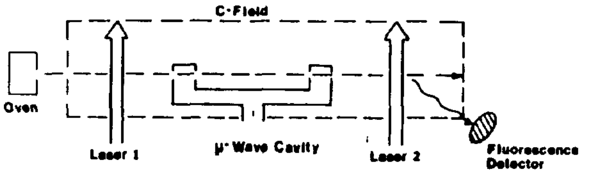

Figure 2. Schematic of an optically pumped cesium beam clock.

More complete pumping into the $|3,0\rangle$ state is possible if two lasers are used for the optical pumping. [7] One laser may be tuned to the ${}^2S_{1/2}$, F=3 $\leftrightarrow$ ${}^2P_{3/2}$, F'=3 transition using π-polarization. This pumps all magnetic sublevels of the F=3 ground state HFS into the F=4 HFS, with the exception of the m_F=0 sublevel. A second laser, tuned to the ${}^2S_{1/2}$, F=4 $\leftrightarrow$ ${}^2P_{3/2}$, F'=3 transition pumps atoms back into the F=3 HFS. After many cycles of this process, most atoms should reside in the F=3, m_F=0 sublevel. Experimental verification for this process has been reported. [5,8]

Optical Detection

In order to detect the number of cesium atoms which made a transition from the F=3 to the F=4 ground state hyperfine levels after the application of the microwave signal (Figure 2), the same laser used for the single-laser optical pumping described above may be applied to the downstream atoms. The fluorescence collected from the atoms is a direct measure of the number of atoms which have made the microwave transition. In this case, approximately two photons per atom are emitted, placing sever demands on the collection efficiency and input noise specifications of the detection optics. An alternative approach is to use another laser tuned to the ${}^2S_{1/2}$, F=4 $\leftrightarrow$ ${}^2P_{3/2}$, F=5 transition. With this transition, atomic selection rules require the excited atoms to decay back to the F=4 level, where they may interact again with the laser light. Since more than 100 photons can be emitted per atom, the collection optics need not be very efficient, and yet the net quantum efficiency of detection will be essentially unity.

Experiment

We have constructed and partially tested two beam tubes. Using the fabrication capabilites at Frequency Electronics and making maximum use of standard parts and geometries it is possible to build small, simple, dedicated tubes in which all the geometrical parameters are fixed. This arrangement has the advantage that its easy and one does not subsequently have problems controlling and adjusting a large number of parameters. However, it has the disadvantage that is hard to go back into an all welded package and correct the inevitable design and assembly errors.

The first device was a minimum modification on an existing commercial beam tube and is schematically shown in figure 3. The "A" and "B" magnets, hot wire ionizer, electron multiplier and vac-ion pump were omitted in construction. Instead vacuum flanges were added at both ends for the addition of test ovens, in the "A" and "B" regions for the addition of the optical pumping and detecting optics and in place of the vac-ion pump so a large vacuum pumping station could be fitted to facilitate repeated openings of the system. The magnetic shields, c-field and Ramsey cavity remained unchanged from the standard commercial tube. The ovens used on this device were of the ideal "dark wall" type (see the accompanying paper on recirculating ovens). The ovens were separated from the beam tube by gate valves which could be closed when the beam tube system was opened. The fluorescence collection optics were a combination of a spherical mirror and an aspheric lens followed by a relay lens which refocused the fluorescence onto a photodiode mounted outside the vacuum envelope. The overall collection-detection efficiency was about 5%.

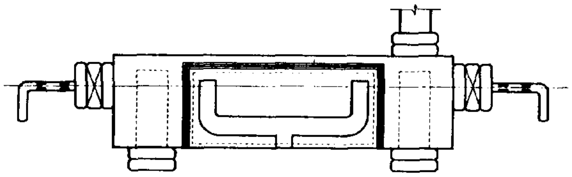

Figure 3. Schematic of OPCS-1.

The second unit differed more radically from a conventional standard as shown in figure 4. The "c-field" and the magnetic shields were extended to include the entire length of the device in an attempt to control magnetic field gradient induced transitions (Majorana transitions). The fluorescence collection optics included a spherical mirror segment facing an elliptical mirror which directly imaged the fluorescence onto a large area photo diode mounted outside the vacuum. The overall collection-detection efficiency was about 35%. As in the first unit, ovens were fitted to both ends. However, unlike the first unit, the ovens were of the standard production type and the total device hard sealed with no vacuum flanges.

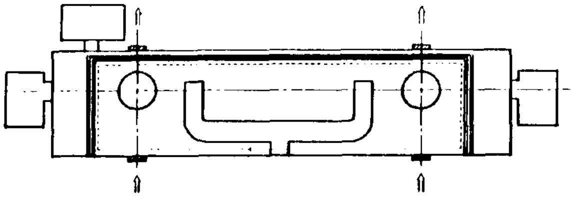

Figure 4. Schematic of OPCS-2.

We have called these two units OPCS-1 and OPCS-2 for "optically pumped cesium standard" numbers 1 and 2. A third device is under construction which will not be functionally different from OPCS-2 except in some of its abilities to generate and study *Majorana* transitions. It will, however, solve some optical problems associated with the hard seal technology used on OPCS-2 as well as employing a superior magnetic shielding package.

The lasers used were of the "channel stripe planer" (CSP) type with simple cleaved facet cavities. However, in this form they proved somewhat mode unstable and excessively sensitive to feedback from other optical elements in the experiment. The solution to this was the use of a flat mirror located as close to the back facet of the laser as the heat sink would allow (about 2 mm) and mounted on the piezo-electric transducer (PZT). This fed back enough light (about 10^{-6} of the back facet emission) to force mode control. Changing the drive voltage to the PZT caused mode changes about every 100 V with broad regions of mode stability in between. When followed by a Faraday isolator with about 30 dB of isolation, this laser system proved mode stable for indefinite periods. The laser system together with its collimating objective and mode control mirror was temperature controlled.

The frequency of the laser was locked by a two level servo to the optical resonance of the cesium beam itself. The laser drive current was modulated at several hundred hertz. The resulting FM produced an AM on the fluorescence from the atomic beam. Synchronous detection then resulted in an error signal which when integrated was used to correct the laser drive current. With a cross over of some 10 seconds, this error signal was also used to control the temperature of the laser and hence keep the drive current centered about a specified value. It appeared subsequently, that through slight alignment errors or residual first order Doppler shift the two lasers could be locked to slightly different velocity groups of the beam atoms and hence introduce an enhanced sensitivity to laser frequency noise that degraded the clock short term stability. The solution to this was to modulate the pump and detection lasers at different frequencies and detect both modulations in the fluorescence emitted from the detection region. That is, just as with the microwave servo system, modulation of the up stream resonance produces a modulated population which shows up at the down stream detector.

Results

All of the results reported here have been obtained using a single laser for state preparation. The detection has always involved the use of the F=4 → F=5 cycling transition. In this case, the slower atoms contribute more strongly to the observed signal by virtue of their greater interaction time with the detection laser. The result is a slightly narrowed Ramsey resonance from that which would be produced by a purely effusive beam (see Figures 5 and 6). That is, a purely effusive beam would have a velocity distribution given by

$$I(v) = \frac{2I_0}{\alpha^4} v^3 e^{-v^2/\alpha^2}$$

where $\alpha = \sqrt{2kT/m}$. However, when detected via an optical cycling transition, the effective velocity profile has the form

$$I'(v) = \frac{2I_0}{\alpha^4} v^2 e^{-v^2/\alpha^2}$$

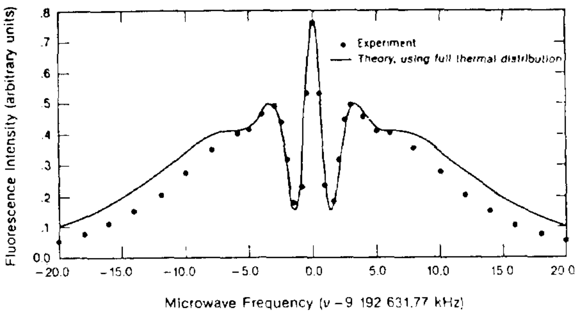

Figure 5. The observed Ramsey resonance fit by a theoretical line shape for a full thermal velocity distribution.

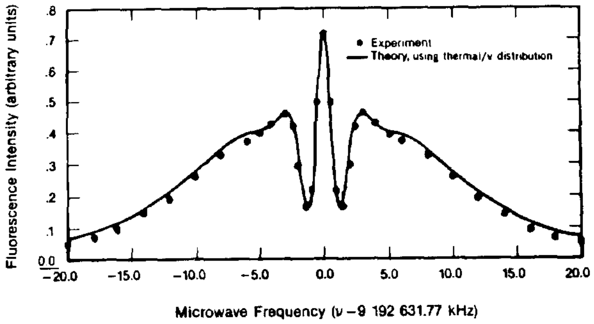

Figure 6. The observed Ramsey resonance fit by a thermal distribution weighted by v^{-1}.

Both OPCS-1 and -2 have been locked up and run as clocks. They both exhibit short term stability $\sigma_y(\tau) \leq 1 \times 10^{-11}\tau^{-1/2}$ for $3 < \tau < 10^4$ s. At longer times the frequency stability of OPCS-1 was dominated by environmental effects which were not carefully controlled in this device. The longer term behavior of OPCS-2 has not been studied.

In OPCS-1 the short term stability was limited by residual FM noise in the diode lasers. The hard seal window technology used in OPCS-2 resulted in a high level of scattered laser light at the fluorescence detector and thus required the use of laser powers well below optical saturation. Also, the lasers used on this device happened to tune to the cesium resonance at relatively low power levels where the laser linewidth and FM noise are comparatively worse than at higher power levels [9]. The result was an initial operating performance $\sigma_y(\tau) > 10^{-10}\ \tau^{-1/2}$ for $3 < \tau < 10^4$ s. When a dye laser with its superior linewidth and FM noise characteristics was substituted for the diode lasers, the stability of $\sigma_y(\tau) < 10^{-11}\ \tau^{-1/2}$ quoted above was obtained. The FM noise of the diode lasers was then reduced by servo control to stable reference cavities and the $\sigma_y(\tau) < 10^{-11} \tau^{-1/2}$ performance was again obtained. In this case the stability was limited by shot noise of the scattered light.

In an attempt to show the potential for sustained operation, OPCS-1 was run uninterrupted for a 45 day period. Also a search was made for frequency offsets in OPCS-1 due to the optical pumping and detection process itself. No frequency shifts at the 10^{-12} level were found. Tests included changing both the pump and detection laser intensities, changing the specific optical transition used for locking the laser frequency, and varying the laser injection current, modulation frequency and amplitude. These results make the possibility of frequency shifts due to light shifts (ac Stark shift) or modulation cross-talk unlikely at the 10^{-12} level. This is consistent with the shift of 3×10^{-14} predicted in the accompanying paper on light shift by J. Shirley.

Conclusions

The optical state preparation process treats all velocity classes equally. As a result, the mean velocity of an optically selected beam is about twice that of a conventional magnetic state selected beam. For the same Ramsey cavity, this results in a microwave linewidth which is about twice as wide. This is the case for the devices studied here. The parent tube has a linewidth of about 800 Hz while the optically pumped derivations of it used here have a linewidth of 1.3 KHz. In spite of this loss of line Q, the increased utilization of atomic beam flux resulted in a substantial overall performance improvement. The conventional parent tube has a short term stability of $\sigma_y(\tau) = 3.5 \times 10^{-11} \tau^{-1/2}$. In the case of OPCS-2 we used the same oven and beam flux and achieved a $\sigma_y(\tau) < 1 \times 10^{-11} \tau^{-1/2}$. However, we are still being limited by phenomena other than the beam shot noise. In fact, the limit for OPCS-2 under the conditions that it has been operated is $\sigma_y(\tau) = 3.5 \times 10^{-12} \tau^{-1/2}$.

Because of experimental problems with the two devices tested so far, we have not studied either the long term stability or the effects on Majorana transition expected from the change in magnetic shielding design used in OPCS-2. The lack of long term stability has prevented a serious test of the theoretically predicted light shift but we have shown the light shift to be below 10^{-12} in OPCS-1. The operation of OPCS-1 as a clock for 45 days shows that there are no problems with the lasers, as operated here, that would prevent long term clock operation.

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