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Design Studies for a High-Stability Laser-Cooled Rubidium Local Oscillator

D. Kujundzic[1]*, S.R. Jefferts, T.P. Heavner and T.E. Parker,*
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80303

Abstract

The combination of a low-velocity intense source (LVIS) for Rubidium (Rb) atoms [1], along with a Ramsey cavity presents interesting alternatives to either traditional beam-type clocks or to the fountain geometry. The basic idea is not new, and much of the original thinking for such a clock has been described previously by Buell and Jaduszliwer [2]. The current study differs in significant detail from the device in Ref. 2. First, the device we describe is much larger than the device in [2] having been optimized for laboratory use as a local oscillator rather than use as a transportable standard. Also, the use of phase modulation allows local oscillator locking at much less than the Ramsey interrogation time. Magnetic deflection of the atoms reduces the complexity of the device while simultaneously diminishing instabilities associated with resonant light. A less significant difference is the use of Rb in place of Cs. The clock should produce stabilities of $\sigma_y(\tau) \sim 10^{-14}\tau^{-1/2}$

Introduction

The combination of a large flux of atoms with high collimation, which can be achieved using a LVIS source and the apparent lack of spin-exchange frequency shifts in Rb, would seem to make the combination a viable system with which to build an extremely low-noise Rb local oscillator.

Results from the original LVIS paper [1] report an atomic beam with a brightness in excess of 10^{12} atoms/sr-s and an angular spread of about 25 mrad Using this beam flux in a Rb standard with a Ramsey length of 100 cm should allow an Allan variance of $\sigma_y(\tau) = 1\times10^{-14}/\ \tau^{1/2}$ to be achieved. If phase-modulation interrogation is utilized the cycle time for attack on an external quartz oscillator will be less than 10 ms.

Proposed Apparatus

The proposed apparatus is shown schematically in Fig. 1. Rubidium atoms are cooled and launched from the LVIS source at the bottom of the figure.

The LVIS atomic source, see Fig.2, is basically a magneto-optic trap (MOT) with a "leak". Atoms are trapped in a MOT with a combination of light pressure and magnetic field gradients (which "tune" the optical resonance frequencies). The light fields in a MOT are typically overlapping counter-propagating beams with opposite helicity. In an LVIS, the overlapping nature of the beams is intentionally interrupted in a small portion of one of the trapping beams, leading to unbalanced light forces on the trapped atoms. This unbalanced force causes atoms to be pushed from the trap in an intense beam. Beam brightness of 5×10^{12} atoms/sr-s has been observed [1].

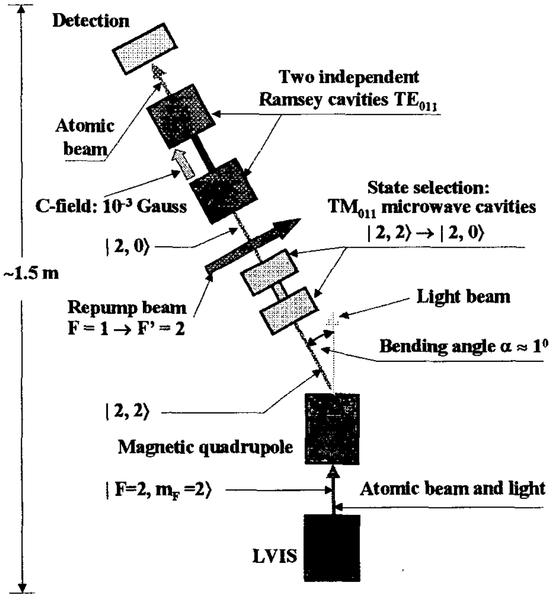

Figure 1 - *Schematic Diagram of the proposed apparatus. The scale is distorted with the bending angle greatly exaggerated and the relative sizes of various parts adjusted for clarity.*

A feature of the LVIS source is that the emerging atoms are coincident with the circularly polarized light beam. In the present case for ^{87}Rb atoms, this means that the atomic beam

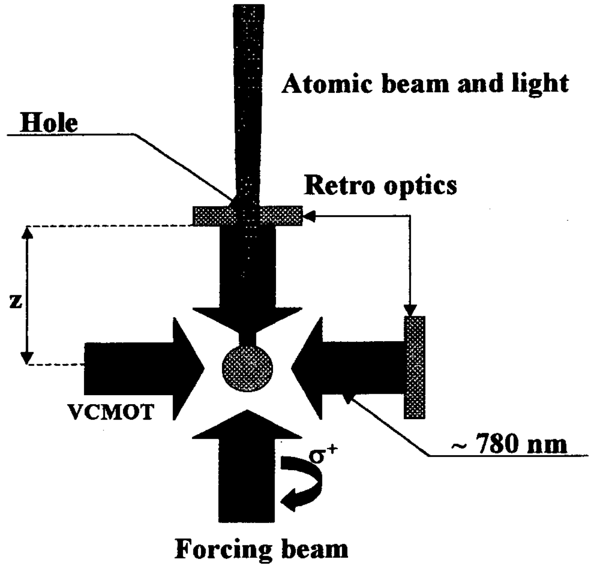

Figure 2 - *Schematic Diagram of the LVIS. Notice that the small hole in the retro-optic has been greatly exaggerated. The proposed device has "z" approximately 3 cm and the diameter of the hole in the retro-optic is 0.6 mm.*

leaving the LVIS should be in the |2,2⟩ state. Unfortunately, without more care the atoms will be optically pumped into the F=1 hyperfine manifold. This can be prevented by re-pumping the atoms as they enter the magnetic quadrupole bender(not shown in Fig 1), thus allowing a polarized |2,2⟩ atomic beam. These |2,2⟩ atoms first encounter a magnetic quadrupole after leaving the LVIS. The atoms are both deflected and focused by the quadrupole. The deflection of about 1 degree effectively removes the atoms from the overlapping light beam by the time the atoms enter the first state-selection microwave cavity also shown in Fig. 1. Actually gravity alone would be sufficient to remove the atoms from the 0.6 mm light beam, however, the quadrupole removes them more quickly, as well as focusing the beam to allow greater detected atomic flux.

In the vicinity of the state-selection microwave cavities the diameter of the atomic beam is less than 0.5 cm, allowing the use of relatively small apertures in the microwave state-selection cavities. The cavities can be built from standard rectangular waveguide as shown in Fig. 3. This has the advantage of being extremely compact while still allowing essentially all of the atoms to be transferred from |2,2⟩ to |2,0⟩. This transfer is effected in two discrete steps, in the first cavity |2,2⟩ atoms are moved to the |1,1⟩ state with a π pulse. In the second cavity |1,1⟩ atoms are transferred to |2,0⟩ in a similar fashion. A weak piece of the re-pump laser from the LVIS may be necessary at this point to destroy any coherence which may have been generated as a result of the selection process. The entire length of the state-selection region can be about 8 cm.

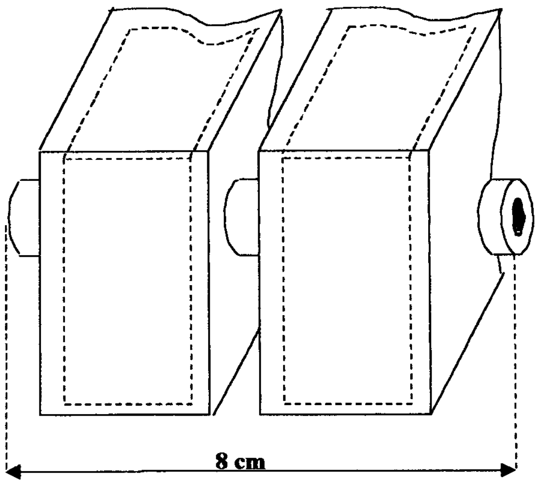

Figure 3 - *The state-selection cavity can be constructed from standard rectangular waveguide. The microwave magnetic field is perpendicular to the C-field allowing Δm=1 transitions.*

The atoms next enter the Ramsey cavity which will have an overall length of about 1 m. The 1 m length coupled with an average velocity of 15 m/s from the LVIS results in a Ramsey line width of δν=7.5Hz. As a result of the focusing of the magnetic quadrupole, the atomic beam leaving the second Ramsey interaction zone has a full-width half

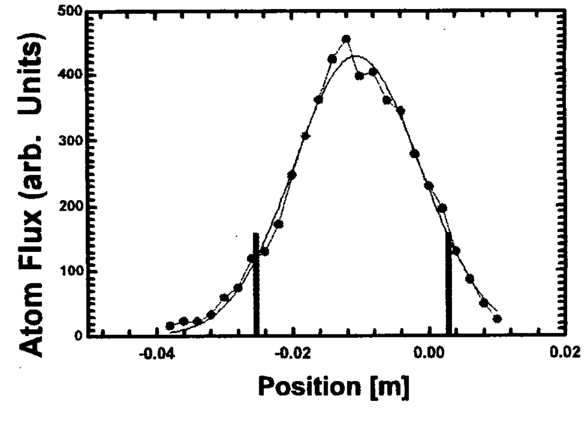

Figure 4 - *This is the modeled atomic flux at the position of the exit aperture of the Ramsey cavity. The solid curve is a Gaussian fit (there is no particular reason to expect a Gaussian, it is simply convenient) with a FWHM width of 2.0 cm, less than the exit aperture diameter of 2.4 cm.*

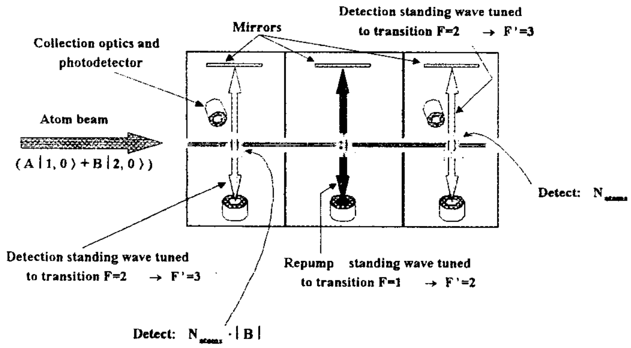

Figure 5 - *The detection system first detects F=2 atoms on the F=2→3' cycling transition and then clears the F=2 atoms with a traveling wave tuned to the same transition. The F=1 atoms are then pumped into F=2 and detected.*

maximum(FWHM) diameter less than the 2.4cm diameter of the cavity apertures (the cavity has a height of 2.5 cm and a diameter of 11 cm). Simulations show that approximately 85% of the atoms entering the Ramsey cavity reach the detection region. We have modeled the beam profile for a number of different configurations of beam bender and beam solid angle. The results in Fig. 4 show the beam profile at the exit of the Ramsey cavity for the case of 20 mrad divergence angle and a Ramsey cavity 1 m long. The cavity apertures are shown as the heavy vertical lines cutting the atomic distribution. The Ramsey cavity will be operated using square-wave phase modulation as described in [3,4]; the implications of this are discussed in a later section of this paper.

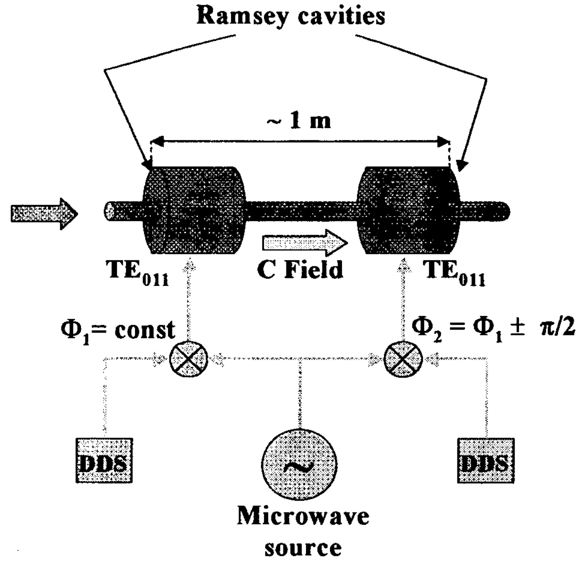

Figure 6- *One possible implementation of the independent square-wave phase modulation scheme in the Rb clock*

Finally the relative populations in F=1 and F=2 must be measured in order to generate an error signal to steer the quartz oscillator. The detection is similar to that used in many atomic fountains, where first atoms in the upper hyperfine state are detected and then removed from the sample with radiation pressure[5]. The remaining atoms in the lower hyperfine state are then pumped into the upper hyperfine state and detected in the same manner as the upper hyperfine state atoms. The process is illustrated in Fig. 5. Using 2mm thick detection beams and a solid angle for detection of 0.12 sr results in about 1.5×10^3 detected photons/atom. Signal-to-noise considerations from this source should be negligible.

Phase-Modulation System

One novel feature of this clock is the proposed modulation scheme. Square-wave phase modulation with independent control of the two Ramsey cavities has been proposed for the PARCS cesium clock destined for installation aboard the International Space Station [3,4]. The motivation for the use of phase modulation in that context is primarily suppression of vibration-induced frequency instability. In the present context the motivation is somewhat different.

In the phase modulation scheme (see Fig. 6) the first Ramsey cavity is driven at the resonance frequency of the

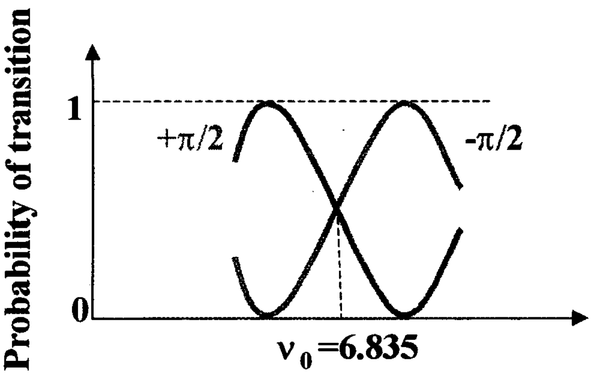

Figure 7 - *The servo error signal is generated by the difference between the present frequency and the frequency at which the +90° phase curve intersects the -90° phase curve.*

hyperfine transition, and the phase of the (microwave) field within the cavity is the nominal zero of phase for the Ramsey interaction. The second cavity is driven by a coherent source of microwaves whose frequency is the same as that in the first Ramsey zone but whose phase is alternately driven to ±90°. This produces two dispersion-like line shapes whose intersection is at the resonance frequency, see Fig. 7. The interest in the scheme for this clock is that the blanking time required for interrogating first one phase and then the other is proportional to the Rabi time, instead of the Ramsey time in the traditional frequency-modulation scheme. This results in an attack on the phase lock to the local oscillator which is almost two orders of magnitude faster than the traditional scheme (L/l), with the added advantage that the duty cycle is also much larger (thereby suppressing the Dick effect).

Expected Performance

If we assume that we can generate the same source brightness as the original LVIS group, 5×10^{12} atoms/sr-s into a 20 mrad divergence beam this yields a flux of 1.6×10^{9} atoms/s. Assuming 50% efficiency in delivering $|2,0\rangle$ atoms to the first Ramsey cavity we have a possible detected atom flux of 0.8×10^{9}.

The TE_{011} microwave cavities have a length of about 2.5 cm which results in a Rabi time of 1.7 ms. In order that the duty cycle be reasonably high the time spent measuring atoms should be at least this long. As a reasonable example, assume a cycle where the time spent measuring is 6.3 ms and the blanking time is then 1.7 ms for a cycle time of 8 ms and a dead time fraction of about 20%. The actual useful detected flux is then reduced to about 5×10^{8} atoms/s.

The shot-noise limited stability of such a clock can be written as

$$\sigma_y(\tau) = \frac{\delta\nu}{\pi\nu_o}\frac{1}{\sqrt{2N_{at}}}\sqrt{\frac{T_c}{\tau}} \qquad \textit{valid for } \tau > T_c$$

where $\delta\nu$ is the linewidth, ν_o is the resonance frequency, N_{at} is the number of detected atoms at the cycle time and T_c is the cycle time. Here, $\delta\nu$ is expected to be about 7.5Hz, ν_o is 6.835 GHz, and the cycle time is 8ms. This allows a possible Allan Variance of $\sigma_y(\tau) = 1\times10^{-14}\tau^{-1/2}$.

Conclusions

We have described a possible architecture for an atomic clock based on a slow beam of Rb atoms. The potential short-term stability is impressive, $\sigma_y(\tau) \sim 10^{-14}\,\tau^{-1/2}$. We have not investigated the long term stability of such a device, but is seems feasible to reach at least the low 10^{-16} range with such a device.

Acknowledgments

The authors acknowledge Bernardo Jaduszliwer and Walter Buell for originally suggesting this type of clock. We also acknowledge fruitful discussions with Bill Klipstein and John Dick of JPL regarding phase-modulation techniques. Leo Hollberg has also contributed to our understanding of the optical processes.

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[1] Permanent address:
Institute of Physics. University of Belgrade Belgrade Yugoslavia.