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Compact CW Cold Beam Cesium Atomic Clock

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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We present a novel cesium beam physics package, which uses optical techniques to combine the high signal-to-noise ratios achievable by optical pumping and beam brightening with the narrow linewidth allowed by a slow atomic beam. Our design can be realized in a compact, robust package suitable for space applications. Our approach differs from other laser-cooled clocks in that we use a cold-atom source that provides a continuous beam. We estimate the shot-noise-limited stability that can be achieved with this physics package to be 2 to 3 orders of magnitude better than that of current compact cesium beam atomic clocks.

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1. Introduction

Laser-pumped cesium beam atomic clocks have been under development over the last 20 years. Optical pumping allows for the utilization of essentially 100% of the atoms in the beam,[1–3] improving the clock signal-to-noise ratio over that of similar beam clocks using magnetic state selection by factors between 5 and 10. Those optically pumped clocks are typically laboratory instruments, with no limitation in size or weight. The last several years have seen feverish activity in the development of cold-atom clocks that exploit laser cooling techniques to implement variations of Zacharias' fountain clock proposal,[4,5] achieving very narrow clock transition linewidths by lengthening the microwave interrogation interval. "Cold-atom" devices intended for use in space are also under development.[6,7] Those devices are fairly complex, and, in principle, their basic design requires cyclic interrogation.

Our objective is to develop a novel cesium beam physics package that will use optical techniques to combine the high signal-to-noise ratio achievable by optical pumping and beam brightening with the narrow linewidth allowed by a slow atomic beam, while operating in a CW manner. We further constrain ourselves to designs that can be realized in a compact, robust package suitable for space applications. Our approach differs from others in that we use a cold-atom source that provides a continuous beam. This will enable continuous interrogation of the physics package, eliminating the enhanced impact of local oscillator noise on atomic clock stability caused in cyclic interrogation clocks by the Dick effect.[8]

2. The Cold-Atom Beam Source

The cold beam source, schematically shown in Figure 1, consists of a magneto-optic trap (MOT)[9] formed with a single circularly polarized laser beam from a 150-mW α-DFB diode laser directed into a right-angle conical reflector.[10] The symmetry center of the magnetic field generated by a set of antihelmholtz coils lays on the axis of the conical reflector and becomes the center of the MOT. Polarization changes upon reflection, combined with the change of sign of the magnetic field at the center of the trap, provide the three-dimensional σ^+ and σ^- counterpropagating light fields required by the MOT.

The reflector is a 5-cm-dia OFHC copper cylinder with a diamond-machined conical inner surface and a protected gold reflective coating of rms surface roughness < 5 nm. At the apex of the cone, there is a 1-mm orifice that creates a "dark column" with no retroreflected light. Atoms are pushed out of the MOT by the incident laser beam, forming a low-velocity, intense source (LVIS) of cold atoms.[11] The LVIS approach results in a continuous atomic beam.

The effective capture radius of our MOT is about 1.5 cm, and the capture velocity is about 20 m/s. The MOT operates on saturated cesium vapor at room temperature; under those conditions, the

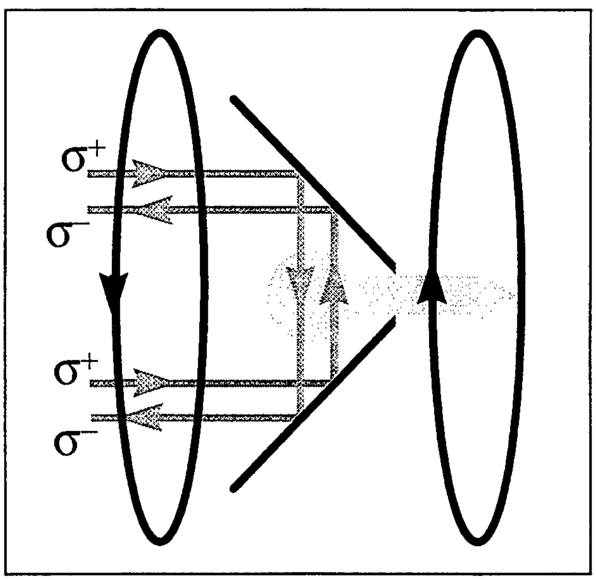

Figure 1. Schematic diagram of the cold cesium beam source, showing the antihelmholtz coils, the conical reflector, the incident and reflected light, the trapping region, and the output atomic beam.

expected MOT loading rate is about 10^8 atoms/s. Since the MOT losses are dominated by transfer to the LVIS beam (and not by collisions), we expect the beam flux to be also about 10^8 atoms/s. The mean speed of the cesium atoms pushed out of the MOT through the 2-cm-long "dark column" will be about 10 m/s, and the velocity spread for a 0.5-cm-dia MOT will be about 3 m/s.

4. The Cold Beam Clock

Our proposed realization of the CW cold beam cesium atomic clock physics package is schematically illustrated in Figure 2. The LVIS reflector will be placed at the source end of the cesium beam tube (CBT), with a suitable cesium reservoir. The antihelmholtz coils will be placed outside the CBT, and a conventional graphite collimator will provide a differential pumping orifice, limit the cesium background pressure away from the LVIS source, and also provide some shielding against MOT light.

Immediately after the graphite collimator, a transverse laser-cooling region, slightly tilted with respect to the LVIS axis, will collimate, brighten, and bend the atomic beam. The bending of the beam will reduce the microwave resonance light shift caused by LVIS light entering the Ramsey cavity. We are investigating several dark-state transient cooling schemes that would perform the optical pumping state preparation of the beam simultaneously with the collimation and bending. Alternately, the state preparation step could come after the collimation and bending step. After state preparation, the intense, slow beam of atoms in the $F = 3$, $m_F = 0$ state will enter a Ramsey cavity similar in size and configuration to those used in commercial cesium beam clocks.

If an additional reduction in the amount of fluorescent light entering the microwave cavity is required to improve the frequency stability of the device, a short inhomogeneous magnetic field

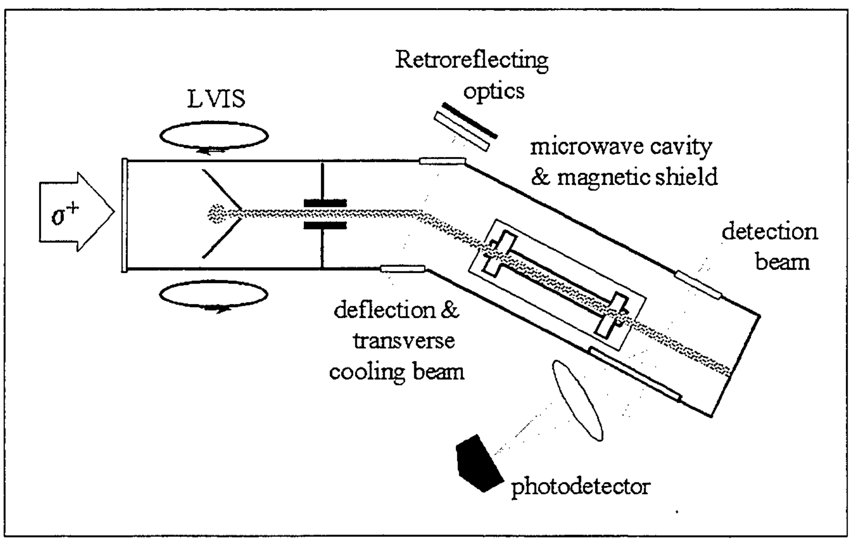

Figure 2. Schematic diagram of the compact CW cold-beam cesium atom clock beam tube. Some obviously needed components such as the cesium reservoir, ion pump, cesium getters and light baffles have been omitted for clarity. The bending angle of the atomic beam (as well as of the beam tube) is exaggerated for clarity.

region can be used for further bending of the atomic beam. In this case, magnetic bending can be accomplished very easily (the atoms are moving slowly) and without significant beam loss (the beam is in a single magnetic state and has a narrow velocity spread).

After traversing the cavity, atoms will be detected by laser-induced fluorescence. With shot noise-limited detection of the 10^8 atoms/s LVIS beam, we expect a signal-to-noise ratio of 10^4. For a mean atomic speed of 10 m/s and a 20-cm Ramsey interaction length, the clock transition linewidth will be about 50 Hz, for a Q of about 1.8×10^8. With those parameters, we estimate that a white frequency noise clock stability $\sigma_y(\tau) \cong 1.1 \times 10^{-13}/\sqrt{\tau}$ will be achievable.

A single 150-mW DBR diode laser will provide the multiple beams required for trapping and repumping the Cs atoms in the LVIS, collimating and bending the Cs beam in the CBT, and detecting the atoms after interrogation. The laser will be offset-locked to a cesium vapor resonance cell. All beams will be fiber-coupled, and electro-optic modulators will provide sidebands with the required offsets, as shown in Figure 3.

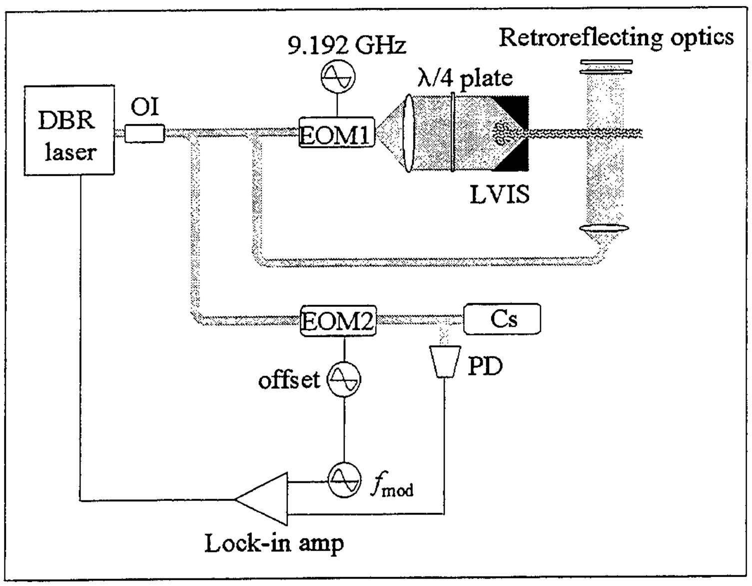

Figure 3. Schematic diagram of the fiber-coupled compact laser system for the clock, using a DBR laser source. OI: optical isolator. EOM1, EOM2: electro-optic modulators. PD: photodetector. Cs: reference Cs vapor cell. The detection laser beam is omitted for clarity.

5. Conclusion

We have discussed the source of a slow, bright cesium atomic beam, and its application to a proposed cold beam cesium atomic clock operating in cw fashion. The beam source has been built and tested.

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