An Optically Pumped Primary Frequency Standard

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An optically pumped primary frequency standard is being constructed at the National Institute for Science and Technology. To achieve the potential accuracy of this new technology a thorough reconsideration of all the potential systematic errors has been undertaken. Based on the needs of the optical pumping process and other improved technologies (ovens and cavities), a unique beam tube has been designed and fabricated. The laser performance necessary to allow full realization of the optically pumped clock's potential has been achieved by an optical feedback technique. The design goal is a short term performance of $\sigma_y(\tau) \leq 5\text{x}10^{-13}/\sqrt{\tau}$ with a total frequency uncertainty of no more than 10^{-14}.

Introduction

The concept of an optically pumped cesium frequency standard is now well established and a number of labs have programs to explore the technology[1-8]. These efforts indicate that an optically pumped primary standard can be constructed such that several of the accuracy-limiting systematic effects in conventional standards can be greatly reduced.

To build such a new standard that will realize its accuracy potential, careful consideration must be paid to all sources of systematic effects. Some of these effects, such as fluorescent light shift, are new to this type of standard. Others, such as those related to the velocity of the atoms in the beam, have been analyzed in conventional standards. However, substantial differences in the velocity profile between conventional standards and optically pumped standards, combined with increased accuracy expectations for the new standard, require that these effects be thoroughly reanalyzed. These studies are outlined in the following section on systematic effects.

The design of the atomic-beam tube must accommodate the optical pumping process as well as adequately address the various systematic effects. The essential features of the new standard are outlined in the section on the beam tube.

Systematic Effects

The systematic effects which have been reanalyzed include: fluorescent light shift[9]; velocity effects to include second-order Doppler shift, shifts vs. RF power and modulation parameters; Rabi pulling; cavity pulling; Majorana effects; distributed-cavity phase shift[10]; RF spectral purity and magnetic field uniformity.

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Many of the shifts can be expressed as the quotient of two velocity integrals containing factors dependent on the microwave power, the modulation parameters and the particular shift mechanism. For very narrow velocity distributions, the velocity average can be ignored, and the power and modulation dependent factors cancel. The shifts then have little or no dependence on microwave power or modulation parameters. An optically pumped standard, however, will use almost all of the broad thermal distribution of velocities emerging from the oven. The shifts then acquire significant dependence on microwave power and modulation parameters. For example, the second-order Doppler shift and end-to-end cavity phase shift can change by 5-10% when the microwave power changes by 1 dB.

Second-order Doppler shifts are calculable if the effective velocity profile, effective microwave power, and modulation parameters are known to adequate accuracy. A numerical method for extracting both the velocity distribution and effective microwave power level from Ramsey lineshapes has been developed and tested with theoretical lineshape data. The agreement of the extracted distributions with the known input distributions is adequate to permit a 1% evaluation of the second-order Doppler shift. Details of the method will be published elsewhere.

Rabi pulling arises from the overlap of other Zeeman components of the hyperfine spectrum when sublevel populations or velocity distributions are asymmetric. When optical pumping is used for state selection, highly symmetric sublevel populations can be achieved. Optical excitation by linearly polarized light creates alignment (symmetric, non-uniform sublevel populations) but not orientation (asymmetric sublevel populations). Orientation can be produced only by pumping with elliptically polarized light traveling along the quantization axis. By using a quantization axis (C-field direction) along the atomic beam and exciting laser beams perpendicular to the atomic beam to eliminate the first-order Doppler effect, even a small elliptically polarized component of the pumping light will not create asymmetric populations. Hence, Rabi pulling should be reduced to insignificant levels.

Majorana transitions, or transitions among the Zeeman sublevels induced by changing magnetic fields, have long been suspected of causing population asymmetries and Rabi-pulling shifts in standards with magnetic state selection[11]. By eliminating the strong state-selecting magnets and performing optical pumping and detection within the shielded C-field region one expects no Majorana transitions. However, if they do occur, either by design or by accident, they should still cause no frequency shifts in an optically pumped standard. The evolution of Zeeman sublevels in a changing magnetic field can be described by the Hamiltonian $\hat{\mu}\cdot\vec{H}(T)$. The evolution operator for this Hamiltonian is a rotation operator. The angular momentum symmetry of rotation operators shows that initially symmetric sublevel populations remain symmetric, no matter what contortions the magnetic field goes through, even if its changes are resonant with the Zeeman frequency. Hence, even an intentionally excited Majorana transition should not shift the clock transition. This will be studied experimentally.

Theoretical studies of the magnetic field generated by a solenoidal winding closely surrounded by side and end shielding indicate that the inhomogeneity arises primarily from the gap between the last winding and the end shield. For a 5 mm gap at the end of a 17 cm diameter solenoid, the on-axis field one diameter from the end is only 0.2% less than that at the center. The inhomogeneity decreases exponentially with distance from the gap. This uniformity is sufficient to use the mean field as measured by the first-order, Zeeman-dependent transitions as a means of estimating the mean square field correction necessary for the clock transition.

Atomic Beam Tube

The design logic for the atomic beam tube and its realization have been described previously[12]. The beam tube is horizontal and of medium length. The heart of the system is a new Ramsey cavity designed to minimize effects of distributed cavity phase shift[10]. The length of the cavity is about 1.5 m and will result in a line Q of 10^8. The microwave field polarization is such as to require a longitudinal C-field. This was chosen to minimize Rabi-pulling effects and to produce a more uniform C-field.

The beam tube is symmetric end to end and designed to allow for simultaneous counter-propagating beam operation[12]. The optical detection zones are 15 cm from the ends of the Ramsey cavity, and the optical pumping zones are 15 cm farther out. This geometry should result in a fluorescent light shift in the 10^{-16} range. The fluorescence collection optics consist of two 5 cm radius mirrors arranged to image the fluorescence into a light pipe which conducts it out of the vacuum envelope to the detector and preamplifier. The system has been shown to collect 45% of the fluorescent light and the imaging properties provide the necessary isolation from scattered laser light.

The atomic beam cross section is 3 mm in diameter, established by the windows in the microwave cavity. The beam is generated in a hybrid recirculating oven[13] with a single 3 mm diameter opening. Operating at 110°C, this oven is expected to generate a beam flux at the detector of 2×10^9 atoms per second while emitting only 30 mg per year of cesium into the beam tube.

Summary

A new cesium atomic beam primary frequency standard which will use optical pumping for state preparation and detection is being built. A thorough reanalysis of systematic effects has led to a design with an expected line Q of 10^8, a short term stability of $\sigma_y(\tau) \leq 5 \times 10^{-13}/\sqrt{\tau}$ and a total frequency uncertainty of 10^{-14}. The laser technology necessary to support this level of performance has been demonstrated[14]. The line Q and accuracy goal place stringent requirements on the line-centering servo. The details of the servo remain an open area of research.

However, the design philosophy is to take advantage of the operational flexibility allowed in an optically pumped system to have a semi-automatic evaluation and to run the standard as a clock. It is expected that RF power, modulation parameters, the effective C-field strength and end-to-end cavity phase shift will be under active control.

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