THE NEW NIST OPTICALLY PUMPED CESIUM FREQUENCY STANDARD

R. E. Drullinger, D. J. Glaze, J. P. Lowe and J. H. Shirley
Time and Frequency Div., National Institute of Standards & Technology
325 Broadway
Boulder, Colorado 80303

Abstract

In this paper we will describe the development, design and preliminary operation of the new optically pumped cesium beam frequency standard at the National Institute of Standards and Technology. The design follows from an analysis of systematic errors found in cesium beam standards. The details of the design, performance of major sub-systems and preliminary results will be discussed.

Introduction

We have previously experimented with optical state-preparation and detection in small prototype cesium beam tubes[1]. These experiments indicate that we can construct a large primary standard which will have exceptional short-term stability and essentially eliminate several of the accuracy limiting systematic errors found in conventional cesium standards.

A project was begun to build a large prototype optically pumped standard capable of continuous clock operation and semi-automatic self-evaluation. However, to build such a new standard and achieve the full accuracy potential, we have had to pay careful consideration to all sources of systematic error. These studies are outlined in the section on systematic effects.

Following from this analysis, the design of the beam tube is outlined in the next section. The laser technology necessary to realize the performance potential is briefly outlined in the section on lasers and the requirements on the controlling electronics are outlined in the final section.

Systematic Effects

The systematic effects which have been analyzed or re-analyzed include: fluorescent light shift[2]; velocity effects to include second-order Doppler shift and end-to-end cavity phase shift as well as their dependence on RF power and modulation parameters; Rabi pulling; cavity pulling; Majorana effects; distributed-cavity phase shift[3]; RF spectral purity and magnetic field uniformity.

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% with a microwave power changes of only 1 dB.

Second-order Doppler shifts are calculable if the effective velocity profile, effective microwave power, and modulation parameters are known to adequate accuracy. However, to predict these from operational parameters seems risky at best. We have developed a numerical method for extracting both the velocity distribution and the effective microwave power level from Ramsey lineshapes. Tests with theoretical lineshape data, even with substantial noise added, show that the extracted distributions are adequate to permit a 1% evaluation of the second-order Doppler shift. Details of the method will be published elsewhere.

Rabi-pulling and Majorana effects should be all but non-existent in this standard, but the theoretical studies give new insight into how these effects enter a standard. These studies are briefly outlined in [4] and more detailed publications are in preparation.

Atomic Beam Tube

The geometry of the new beam tube is outlined in figure 1. The device is totally symmetric about the central microwave feed point and only half the tube is shown here for clarity. The design logic and major sub-systems have been described previously[5]. The Ramsey cavity is a new concept, designed to minimize distributed-cavity phase shift and Rabi pulling[3]. The fluorescence collection optics are large radius, spherical mirrors which collect 50% of the fluorescent light and inject it into a light guide for detection outside of the vacuum envelope. The imaging nature of this system provides the necessary high selectivity against scattered light. All laser optics are external to the beam tube. The laser beams enter and exit through laser-quality, normal-incidence, AR-coated windows.

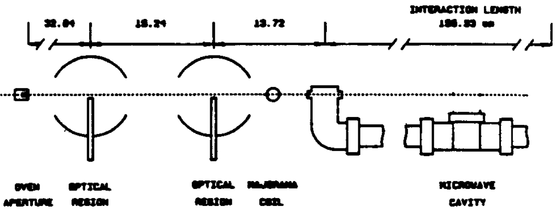

Fig. 1 Schematic of one end of the beam tube

The C field is axial and extends over the entire length of the standard. Three layers of passive magnetic shielding provide a static, axial-shielding factor of 6 x 10^3. This will be electronically enhanced by a servo on the C field (see below).

The atomic beam is 3 mm in diameter and is derived from a new oven design with a recirculating collimator[6]. This oven, operated at 110°C, will produce a flux of 5 x 10^9 atoms/s at the detector while its total cesium emission is only 20 mg/year.

Laser Systems

It has been shown that simple, "off-the-shelf" laser diodes with their inherent FM noise and resulting linewidth of 10's of MHz are incapable of supporting optically pumped clock operation at full, atomic-shot-noise-limited performance[1]. To deal with this we have developed a laser line-narrowing technique based on optical feedback from a high Q cavity[7], Fig. 2.

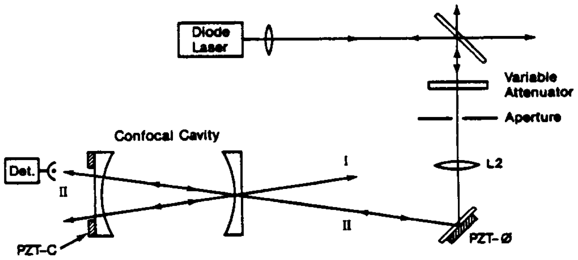

Fig. 2. Scheme for laser line narrowing by optical feedback from a cavity.

With this line-narrowing technique, we have demonstrated nearly atomic-shot-noise-limited performance in an optically pumped standard[8].

Control Electronics

The design of the beam tube produces a clock-signal line Q of just over 10^8. In combination with the clock accuracy goal of a part in 10^{14}, this sets a requirement on the frequency control servo to accurately find line center to better than a part in 10^6. To achieve this accuracy in a traditional, linear (sine-wave-phase-modulation) servo has required the development of a new modulation technique which has second harmonic distortion below -120dB[9]. We will use this servo in our initial operation of the new standard.

However, as pointed out in the section on systematic effects, optically pumped standards are comparatively sensitive to changes in microwave power. Furthermore, our choice of an axial C-field combined with the reduced axial shielding effect of long cylindrical shields produces an undesirable sensitivity to the magnetic environment. To solve these problems and to provide the self-evaluating capabilities possible in this standard, we plan to develop a digital servo which will interrogate the cesium spectrum in ways that will allow it to control the clock frequency, the microwave power, the effective C-field value, the end-to-end cavity phase shift and various electronic offsets.

Summary

We have developed an optically pumped, cesium-beam primary frequency standard. We plan to use this device to study the physics of AC stark shifts as well as Majorana effects. The device is designed to run continuously as a clock and will be nearly self evaluating.

References

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