FORTY-FOURTH ANNUAL SYMPOSIUM ON FREQUENCY CONTROL

OPTICALLY PUMPED PRIMARY FREQUENCY STANDARDS

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Abstract

The use of optical state preparation and detection in atomic beam frequency standards offers tremendous potential for improved short term stability, evaluation and control of accuracy-limiting systematic errors. This paper reviews optical pumping as it pertains to primary frequency standards. The potential benefits and limitations are discussed as is present work on the technology.

Introduction

The development of efficient, inexpensive, tunable, and long-lived diode lasers has made primary clocks with optical state preparation and detection a realistic possibility. Optical state preparation has advantages over conventional magnetic state selection. Magnetic state selection discards most of the atoms in the beam, whereas with optical state preparation, nearly all of the atoms in the beam can be used. This improves the short-term stability of the clock. Optical pumping also produces a homogeneous atomic beam without the spatial velocity dispersion caused by magnetic state selection. The spatial velocity dispersion leads to one of the major accuracy-limiting systematic errors in conventional primary standards. Finally, the replacement of the opaque hot wire detector with a transparent optical detection region makes it possible to run simultaneous counter-propagating atomic beams. This feature, when combined with a frequency control servo system capable of interrogating various parts of the cesium spectrum, makes possible automatic evaluation during continuous clock operation.

The potential for improved accuracy and stability available with this technology has been widely recognized for over a decade, and nearly every national metrology laboratory has at least some effort to investigate it. However, only four labs have efforts involving large, potentially high performance machines. The Communication Research Laboratory in Tokyo is building a machine with about a 1 m interaction length[1]. The National Research Laboratory of Metrology near Tokyo has an operational unit of about the same size which has been evalutated at about 10^{-13} [2]. The Laboratoire Primaire du Temps et des Frequences in Paris is also building a device which is designed to operate at an accuracy of 10^{-13} [3]. The National Institute of Standards and Technology in Boulder is building a device which is designed to become an operational standard with an accuracy of 1 part in 10^{14}. The development of this standard will be used in subsequent sections of this paper to illustrate the technology.

Optical state preparation and detection will be discussed in the first section and used to explain the potential benefits and limitations of this new technology. The potential of these standards for accuracy, combined with their different operational characteristics, has required a careful re-analysis of all errors found in such a standard. This work is outlined in the section on systematic errors. Atomic beam tube design has followed from the error analysis and is briefly described in the next section. Limitations on achievable performance resulting from laser FM noise problems and some solutions are outlined in a section on lasers. Finally, there is a section which discusses some of the requirements on supporting electronics which control the clock frequency and other parameters.

Optical Pumping

Optical pumping to replace state-selecting magnets was first suggested by Kastler[4] in 1950. But it was not practical until tunable lasers were developed. There are a number of ways optical state preparation and detection can be applied in cesium beam tubes and they have been previously described[5-13]. Reference 13 presents an analysis of the various D_2 transitions and gives pumping rates and efficiencies. To illustrate the process, three specific cases will be briefly outlined here. Figure 1 schematically shows two of the electronic energy levels of cesium, the ground state which contains the hyperfine/clock transition and a low lying excited state. An example of the simplest kind of optical pumping would be if the frequency of a laser were tuned to excite the transition $F=4 \rightarrow F'=3$. The $F'=3$ atoms decay back to the ground state in a few nanoseconds. Most go into the $F=3$ state but some return to the $F=4$ state and are excited again. In this way the

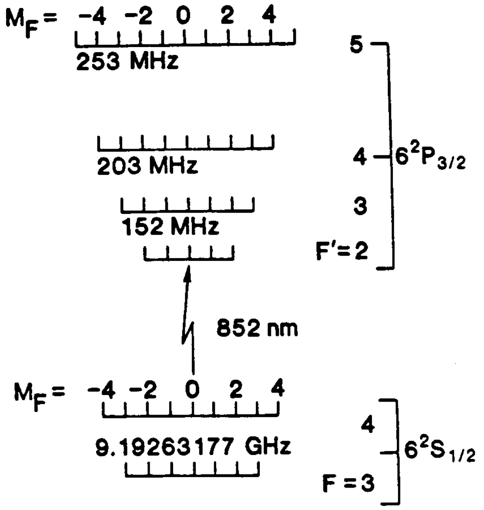

Figure 1. Energy levels of the cesium D_2 transition.

F=4 level is quickly emptied of its population. A slightly more complicated scheme makes use of two lasers[14]. If in addition to the first laser a second laser is used to simultaneously excite the F=3 → F'=3 transition with π polarization, then the atoms are pumped back and forth between the F=3 and F=4 states. However, due to the atomic selection rules applicable to this case, atoms in the F=3, $M_F=0$ substate cannot interact with the laser radiation and are trapped. As atoms in other substates are forced to jump back and forth between the F=3 and F=4 states they sometimes fall into the trapped state. In this way, the population from all 16 substates can be manipulated into the one substate which is the source state for the clock transition. The last example is that of a cycling transition which can be used to advantage for detection. Because of the selection rule $\Delta F = 0, \pm 1$, tuning the frequency of a laser to the transition F=4 → F'=5 will produce excited atoms which can decay only to F=4, the state from which they came. In this way the atoms can be excited many times thus insuring their detection by the decay fluorescence.

The advantages and limitations of this technology can now be understood with the aid of the hypothetical clock schematic shown in Figure 2. In this case, 1 or 2 lasers are used to prepare the atomic beam for "clock interrogation." The state-prepared atoms then pass through a conventional Ramsey interrogation zone. Finally, those atoms that make the clock transition can be detected with essentially unit probability by detecting the fluorescence generated in a laser-driven cycling transition which is specific only to atoms in the clock's terminal state.

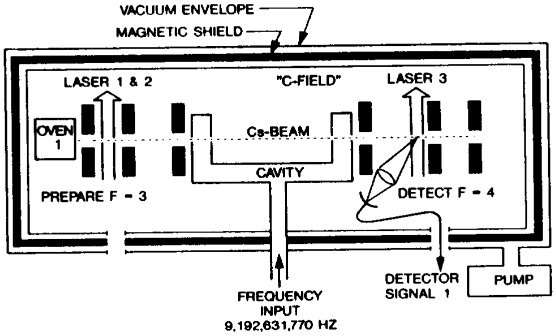

Figure 2. Schematic diagram of an optically pumped, atomic beam frequency standard.

This form of state preparation as opposed to magnetic state selection more efficiently uses the atomic beam flux. For the same atomic flux from the oven, optical pumping can produce or prepare more than 100 times more atoms in the initial clock state than many common magnetic selection schemes. This improved beam flux can directly result in improved short term clock stability.

Other advantages of optical state preparation have to do with accuracy and long term stability of the clock. Optical state preparation does not produce the spatial velocity dispersion in the atomic beam that magnetic state selection does. This comes into effect in the evaluation of end-to-end phase shift, one of the major systematic errors in primary standards. End-to-end phase shift is the result of physical imperfections in the microwave cavity which give rise to a difference in the microwave phase at the two ends of the cavity. This phase difference produces a frequency bias in the standard which is traditionally evaluated by reversing the atomic beam. In magnetically state-selected standards the precision of the beam reversal is limited by the spatial velocity dispersion in the atomic beam. With the homogenous atomic beam produced by optical state selection, the evaluation of cavity phase shift can be performed with greater precision. In fact it can be done in real time without interrupting clock operation.

Figure 2 shows that a second oven can be added to the opposite end of the machine and a counter-propagating atomic beam generated. The two atomic beams can run simultaneously because the flux in each beam is so tenuous that the atoms do not collide. This fact can be better realized if we consider just the velocity spread in one beam. There is a great dispersion between the fastest atoms and the slowest atoms; the faster atoms are constantly overtaking the slower. If the flux were great enough to allow collisions, we would see the results in one beam alone. The atoms in the second beam can pass through the detection zone for the first beam with no interaction (and vice versa) if they are first optically pumped into the F=3 state. In this way the beam reversal can be done without clock interruption.

Another systematic error can be caused by a spectral line overlap problem known as Rabi tail pulling[15]. The magnetic substate structure of the cesium atom results in a multi-line spectrum on the hyperfine transition. While these lines can be completely resolved spectroscopically, the precision with which the microwave frequency is servoed to the center of the central feature in this spectrum produces a sensitivity to the small residual overlap of the adjacent line wings. In a conventionally state-selected device the population in the magnetic substates is asymmetrically distributed in a way that causes an imbalance in these overlap shifts. Single-laser state preparation, on the other hand, leads to a symmetric spectrum with a cancelation of overlap shifts, and two-laser state preparation eliminates the population in the other substates altogether. This not only improves the accuracy of the clock but gives it added stability against environmentally caused changes in microwave power and magnetic field.

Finally, the elimination of the state-selecting magnets allows the uniform C-field region to be expanded to include the optical state preparation and detection regions. This eliminates Majorana transitions (magnetic field gradient-induced transitions) and frequency errors that may come from them.

All of these potential benefits do not come without limitations. The very aspect of the optical state preparation that gives no velocity selection or dispersion results in a very broad velocity spread in the atomic beam and a comparatively high mean velocity. The slow atoms remain in the microwave field longer than the faster atoms. While the fastest atoms may not be in the field long enough to make the clock transition, the slowest atoms may make the transition, then make it again, and finally end in the starting state. The velocities at which these effects occur are a function of the microwave power and modulation parameters. The result is a slight velocity selectivity that couples microwave power and modulation parameters to the clock frequency through the second-order Doppler shift and cavity phase shift. This effect will show up in the long term stability of the standard. One way to reduce this potential problem is to use modern electronics to manipulate the frequency of the microwave source in ways that produce information about these parameters directly from the cesium spectrum. This will make it possible to operate these parameters under closed loop control.

A new source of error in an optically pumped standard is caused by the fluorescence which comes from the state preparation and detection zones. Some of this light travels directly along the atomic beam path and is present during the interrogation of the clock transition. The result is an AC Stark shift of the hyperfine energy levels. Fortunately, the effect is small and is easily controlled to a level below 1 part in 10^{15} through the choice of geometry and operational conditions[16].

Systematic Effects

The systematic effects which have been analyzed or re-analyzed include: fluorescent light shift[16]; velocity-dependent effects such as second-order Doppler shift and end-to-end cavity phase shift including its dependence on RF power and modulation parameters; Rabi-pulling; cavity pulling; Majorana effects; distributed-cavity phase shift[17]; RF spectral purity and magnetic field uniformity.

Many of the shifts can be expressed as the ratio of two integrals over the velocity distribution 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 to 10% with microwave power changes of only 1 dB.

Second-order Doppler shifts are calculable if the effective velocity profile of the atoms contributing to the signal is known to adequate accuracy. The broad velocity spread in an optically pumped standard not only results in a sensitivity to microwave power but produces a Ramsey resonance with less structure (information content) than conventionally state-selected devices. This has rendered some traditional velocity measurement techniques inadequate. However, a numerical method for extracting both the velocity distribution and the effective microwave power level from Ramsey lineshapes has been developed[18].

Rabi-pulling and Majorana effects should be extremely small in optically pumped standards, but the theoretical studies give new insight into how these effects enter a standard. These studies are briefly outlined in [19], and more detailed publications are in preparation.

Atomic Beam Tube

Optical state preparation and detection offer potential for improved control of the clock resonance line-shape physics primarily through the elimination of magnetic field gradients and spatial velocity dispersion in the atomic beam. The beam tube design should take full advantage of this potential.

Any magnetic field gradients can be nearly eliminated by extending the C-field region to include the entire clock. The non-velocity dispersed atomic beam offers the potential for better beam retrace precision during beam reversal evaluation of end-to-end cavity phase shift errors. Retrace precision is necessary to avoid a sensitivity to distributed cavity phase shift which is not directly evaluated. To realize the full potential of this attribute of optical pumping, a new Ramsey cavity has been developed to minimize the distributed cavity phase shift[17]. Finally, the geometry must be chosen to allow complete evaluation and not produce an unacceptable "fluorescence light shift."

The NIST beam tube is shown schematically in Figure 3. The beam tube is totally symmetric about the central microwave feed point, so only half the tube is shown. The design logic and major sub-systems have been described previously[20]. An axial C-field has been chosen to minimize Rabi-pulling[15], provide a more uniform field and to facilitate the new Ramsey cavity. 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 the vacuum envelope. The imaging nature of this system provides high selectivity against scattered laser light. All laser optics are external to the beam tube.

Laser Systems

Simple, off-the-shelf laser diodes with their inherent FM noise and linewidths of many megahertz are incapable of supporting optically pumped clock operation at full atomic shot-noise-limited performance[21]. To solve this problem a laser line-narrowing technique based on optical feedback from a high-Q cavity has been developed[22]. With this line-narrowing technique, essentially atomic shot-noise-limited performance in an optically pumped standard has been demonstrated[23].

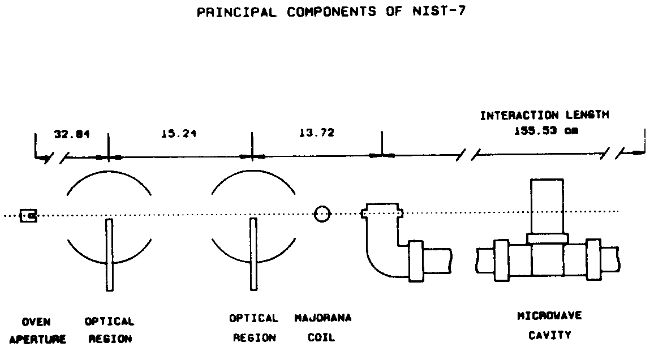

Figure 3. Schematic diagram of NIST-7.

Control Electronics

As pointed out in the discussion of optical pumping, the mean atomic velocity and the velocity spread are greater in optically pumped standards than in most magnetically state-selected standards. This results in a somewhat limited line Q since arbitrarily long beam tubes present other engineering problems, for example, structural, thermal, magnetic and gravitational. The limited line Q combined with greater accuracy goals places a severe burden on the accuracy of the frequency control servo electronics. Additionally, because of the higher sensitivity to microwave power and the higher accuracy we would like to servo such things as microwave power and C-field, which have always been run open-loop in conventional standards. These requirements seem most easily met by a computer-controlled servo that could interrogate the cesium spectrum and develop information about the magnetic field and the microwave power as well as frequency offsets. Correspondingly, for ease of implementation, such a servo would most logically use a slow square-wave modulation scheme. When optical pumping was first considered for use in high performance primary standards, however, such a modulation scheme was not a possibility because the phase noise in available crystal oscillators was too high[24-25]. Fortunately, crystals of adequate performance have recently become available[26].

Conclusions

The technology of optically pumped primary frequency standards should place standards of frequency and time solidly at an accuracy of 10^{-14}. This performance is achievable as a result of the improved short term stability and added control over accuracy-limiting systematic errors. However, the high mean atomic velocity and the broad velocity spread that result from optical state preparation leads to a limited line Q and comparatively high sensitivity to microwave power. Consequently, to achieve a 10^{-14} accuracy places an extreme burden on the servo electronics, and further improvement in accuracy with thermal atomic beams may not be readily forthcoming. Fortunately, photon pressure cooling and cooled, non-thermal beam technology are rapidly advancing, and new standards should soon be available which overcome these limitations[27].

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