Frequency Standards Based on Optically Pumped Cesium

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Invited Paper

The state of development of optically pumped cesium-beam frequency standards is reviewed. The replacement of magnetic methods for atomic state selection and detection by optical (laser) methods provides potential for major reductions in systematic errors as well as a large increase in useable atomic beam flux. These translate to higher accuracy and better stability (both short and long term) or longer operating life if the beam current is reduced. With current technology it appears possible to construct a laboratory primary standard based on the concept. Simple and inexpensive field standards can also benefit from the optical pumping technology, but additional improvements in stabilized laser diodes will be needed.

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I. Introduction

The present definition of the second is based on the frequency of the ground-state hyperfine transition in cesium. As such, all existing *primary* frequency and time standards use a cesium atomic beam, magnetic resonance spectrometer for the realization of the second. The technology employed and the present state of the art are reviewed in other articles in this issue. Although major improvements in accuracy and stability have been achieved, the basic technology has not changed in any material way since Ramsey [1] introduced his scheme of separated oscillator fields. With thirty years of engineering development devoted to the implementation of the technology, it is unlikely that further engineering refinements will yield substantial improvement over the present performance levels. The advent of tunable laser sources, however, particularly diode lasers, makes possible the replacement of the traditional state selecting magnets and hot wire detector with regions of optical pumping. This, in turn, affords the possibility for much better stability and control of accuracy limiting systematics. This paper will review these possibilities and describe some preliminary results obtained to date.

II. The Optical Pumping Process

The use of optical pumping to replace state selecting magnets was first suggested by Kastler [2] in 1950. It was not made practical, however, until tunable lasers were developed. There are a number of ways the process can be applied to advantage in cesium-beam tubes and they have been previously described [3]–[10]. Briefly and in the language of Happer [11] it is a process of depopulation pumping. That is, through the frequency or polarization selectivity of the exciting light, atoms in some states more efficiently absorb the light than atoms in other states. The excited atoms so created can in general relax to several of the various ground-state levels hence depopulating the state from which they started. A variation on this which requires two different exciting light frequencies [4] can convert atoms from 15 of the 16 substate in the cesium ground state into the one substate which is the source state for the clock transition; thereby increasing the utilization of cesium atoms a factor of 16 over magnetic state selection. Furthermore, because of the velocity dependence of magnetic state selection, most conventional state selectors use only a portion of the available Maxwellian velocity distribution. The optical pumping process can be either very velocity selective for diagnostic purposes or totally nonselective for a further increase in beam atom utilization.

III. Prospects

The accuracy limiting systematic error in all conventional cesium-beam frequency standards is the uncertainty in end-to-end cavity phase shift. The standard method to determine this error is to reverse the beam. However, the velocity-dependent trajectories of atoms through magnetic state selectors limit one's ability to precisely affect retrace. In an optically pumped standard, the atomic beam cross section is homogeneous; all parts of the beam contain the same velocity distribution. Hence, precise retrace is more easily attained. In fact, it should be possible to run counter propagating beams simultaneously to continuously monitor and perhaps servo control the end-to-end phase shift.

The question of Majorana transitions can be essentially eliminated in an optically pumped standard. With the removal of the large state selecting magnets, the quantization axis defining field (C-field) can be extended to include the regions of state preparation and state detection; thus eliminating significant magnetic field changes along the atom's flight path. The use of two lasers mentioned above to pump all the atoms into a single substate will reduce the microwave Zeeman spectrum to a single bright line. This will greatly reduce any systematic error due to line asymmetry resulting from overlap with the tails of adjacent Zeeman transition [12]. It will also allow the use of smaller, more controllable C-field values.

The one new systematic error introduced by the optical pumping process is an ac stark shift of the clock transition induced by fluorescent light from the optical pumping regions. Theoretical studies have shown the shift to be small and manageable through device geometry [13].

The introduction of this new technology to both laboratory and field standards should produce marked improvement in device performance. In laboratory standards, the improved control over accuracy limiting systematics should result in fractional inaccuracies of $\leqslant 10^{-14}$ as well as a substantial improvement in the available diagnostics used to study systematic errors. The potential for improved signal-to-noise ratio through increased atom utilization will allow the accuracy and flicker limits to be studied in shorter measurement times.

The potential for portable standards is even greater. The possibility of counter propagating beams together with microprocessor control can make small devices self-evaluating. This, in turn, can mean feedback control over the long-term, stability-limiting systematic errors. Also, the potential for increased beam utilization promises 100 times greater effective beam flux than found in portable devices manufactured today. The combined effect of these two factors is that a beam tube only 0.5 m long could equal the performance of some of our best laboratory standards of today.

IV. Results

Realization of these tantalizing potentials, however, will require some further development in the field of diode lasers. The first optical pumping by a CW diode laser was reported in 1974 by Picqué [14] but his laser had to be operated near liquid-helium temperatures. Since that time, room-temperature laser diodes have been developed, largely for the communication industry. These have exceptionally long lives (10^6 h MTBF estimated) [15] and require only 0.1 W of electrical power. Without modification these devices have been used in two important demonstrations. Using a single laser for state preparation such that about 15 percent of the atomic beam flux contributed to the clock transition, a small beam tube with a 7.5-cm-long Ramsey cavity was operated as a clock and demonstrated a short-term stability of $\sigma_y(\tau) = 10^{-11}/\sqrt{\tau}$ [16]. In another demonstration using the two-laser technique, 98 percent of an atomic beam was pumped into a single magnetic sublevel [10]. Neither of these demonstrations, however, reached the limit of clock performance given by the atomic beam flux. The reason for this seems to be related to the frequency noise of the laser diodes.

The spectral characteristics (linewidth and FM noise) of simple cleaved facet laser diodes as they exist today do not seem to be adequate to fully realize the potential for clock operation as outlined above. In a laboratory environment the solution to this matter is rather straightforward if somewhat complicated. Extended external cavities using the optical diode as a gain element and other frequency control elements such as used in a dye laser can produce the desired spectral characteristics. This type of solution is probably too cumbersome and expensive for field portable clocks. However, diode laser technology is advancing rapidly and, if a solution to these problems does not already exist, it certainly appears within reach given adequate development motive.

V. Conclusions

Optically pumped cesium time and frequency standards using laser diodes offer great potential for improved performance of both laboratory and portable standards. The technology appears to be in hand for the realization of this potential in laboratory based standards but some further laser development is required before the ultimate potential of field standards is reached.

References

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