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THE DEVELOPMENT OF A YTTERBIUM ION FREQUENCY STANDARD*

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Abstract

A ytterbium ion standard is currently under development at JPL for both ground and space applications. We have chosen the ytterbium ion for its large hyperfine splitting of 12.6 GHz, and the accessibility of its first excited electronic energy levels with light from frequency-doubled semiconductor and solid state lasers. In this paper we discuss the desired characteristics of a space-borne instrument and why we have chosen ytterbium to meet these characteristics. We also present the results of spectroscopy carried out on trapped ytterbium ions to determine means for overcoming the population trapping difficulties associated with this ion.

Introduction

Recent progress in the development of trapped ion standards has led to the realization of instruments rivaling the stability of any other microwave standard. The trapped mercury ion standard has achieved fractional frequency stability of $1 \times 10^{-13}/\sqrt{\tau}$ for 150s $\leq \tau \leq$ 10,000s and has made possible stabilities of 2×10^{15} at 24,000 seconds of averaging time, which is unsurpassed by any other frequency standard [1].

Since the inherent stability of the trapped ion standard is inversely proportional to the product of the line Q and the signal- to-noise ratio (SNR), it is desirable to have both high line Q's and high SNR for the highest stability. The mercury ion standard has achieved a line Q of 2.4×10^{12}, the highest ever observed in a microwave transition [1]. Despite this remarkable performance further progress in improving the stability of a field-ready mercury standard is hampered by the requirement of a mercury lamp and associated optics to produce the 194 nm optical pumping light. Optical pumping with lasers greatly improves the SNR, allows higher detection efficiency and replaces complex optical systems with fiber optics. Such an approach is not currently feasible for use with a field deployable mercury ion standard, since generation of light at 194 nm with a laser is complex.

In order to realize the advantages associated with the use of lasers in optical pumping of trapped ions, we have embarked on the development of a standard based on the 171 isotope of singly ionized ytterbium. The hyperfine transition of the ground state of this ion has a relatively large frequency, allowing large line Q's. Furthermore, the lowest lying excited electronic energy levels of the ytterbium ion are accessible with light from frequency doubled semiconductor and solid state lasers, thus making this ion species a desirable candidate as a laser-excited standard.

Another major advantage with laser-excited ytterbium is the potential for the development of a spaceborne trapped ion standard for spacecraft science investigations. With semiconductor lasers and optical fibers, it is possible to reduce the size and mass of a trapped ion standard and realize an instrument with stability comparable to hydrogen masers.

Laser excitation also offers the potential for cooling the ions. Reducing the ions' motion in this way causes a decrease in the second-order Doppler shifts, which generate the greatest frequency offset in a trapped ion standard [2]. Reducing this offset equivalently reduces the stringent stability requirements of several trapping parameters, such as trap field strength, endcap voltage and temperature.

Despite its apparent advantages, ytterbium has difficulties associated with population trapping in lower lying metastable states which must be continually depopulated with additional light sources [3-9]. We have

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performed a great deal of spectroscopy on trapped ytterbium ions and have determined several effective means to depopulate these lower lying metastable states with available semiconductor lasers.

In this paper we will describe the need for a laser-excited trapped ion standard, with emphasis on design requirements for space applications. The status of the standard and the challenges associated with ytterbium will then be reported.

Requirements of Ultra-Stable Frequency Standards in Space

Placing atomic frequency standards with long-term stability in space will significantly improve a variety of radio science experiments. The long-term stability of the radio link between an earth-based receiver and a spacecraft can be severely degraded due to the delay changes induced by random tropospheric variations. At Ka-band frequencies, the greatest noise source for low frequency gravitational wave searches using the earth and distant spacecraft will be due to the troposphere [10]. The tropospheric noise can be removed by simultaneously combining Doppler data generated by a spacecraft clock with data at the earth station [11].

Other experiments which could benefit from space-borne frequency standards include gravitational red-shift measurements [11], and general relativity tests such as testing the isotropy of the speed of light. Space interferometers consisting of two or more spacecrafts with highly stable and synchronized standards would also benefit from space-borne standards with ultra-high stability.

A science instrument suitable for use in space must be easily integrated into a spacecraft and be highly reliable while still accomplishing its primary function. For a frequency standard this primary function is ultra-high stability, on the order of 10^{-15} at 10,000 seconds of averaging time. The hydrogen maser is the only high-performance frequency standard to fly aboard a spacecraft, achieving stability of 10^{-14} at 400 seconds on a flight whose duration was approximately two hours. This test was conducted in 1976 and confirmed the gravitational red shift to 70 parts/million [11]. The Hg^{+} trapped ion standard has already achieved the required stability and high reliability; however, as mentioned earlier, the 194 nm radiation necessary for optical pumping cannot be conveniently generated with laser systems. The use of a mercury lamp provides a simple solution, but requires a significant amount of power and creates a large amount of background noise due to light scattering in the trap.

The desirablilty of a laser-excited trapped ion standard stems from the potential increase in the signal to noise ratio and line Q associated with the use of coherent light. Since the fundamental stability of a trapped ion frequency standard is given by

$$\sigma(\tau) \propto \frac{1}{Q_\ell} \frac{1}{SNR} \frac{1}{\sqrt{\tau}} \quad (1)$$

it is evident that increasing the line Q and SNR are the only approaches for improving the intrinsic stability of the standard.

In addition, the use of lasers conveniently lends itself to the application of fiber optics which in turn relieves design problems in introducing light into the trap. All this leads to a standard of greatly reduced size without compromising stability. Such a standard could weigh less than 15 Kg, fit in a volume less than 30 liters, only consume $\sim$ 20W of power, and could remain in operation for several years. These physical characteristics are comparable to current spacecraft fields and particles instruments. In comparison, a future space maser being developed by the In Space Technology Experiment Program weighs $\sim$ 40 Kg, occupies $\sim$ 130 liters, consumes $\sim$ 30W, and is being designed to last six months [12].

Characteristics of the Ytterbium Ion Standard

The ytterbium ion has a hyperfine structure similar to the mercury ion, with an energy splitting corresponding to 12.6 GHz (see Fig. 1), as compared to mercury's 40.5 GHz. With laser excitation of ytterbium, very high Q's are obtainable, as has been demonstrated by D. Schnier et. al. [4]. These authors obtained a 16 mHz linewidth for the hyperfine transition in $^{171}Yb^{+}$, which corresponds to a line Q of 8×10^{11}.

Another major advantage achievable with laser-excited ytterbium is the ability to cycle the ions on the transition. This will allow scattering of many optical photons for each microwave photon absorbed, thus further increasing the SNR. The cycling of the ($^2S_{1/2}$,F=1) $\leftrightarrow$ ($^2P_{1/2}$,F=0) transition is possible due to the narrow linewidth ($\sim$ 10 Mhz) of the laser and the large 2.1 Ghz hyperfine splitting of the $^2P_{1/2}$ state.

In contrast to the case of the mercury ion, the first excited electronic energy levels of the ytterbium ion are accessible with light from frequency doubled semiconductor and solid state lasers. For example, the transition from the ground $^2S_{1/2}$ state to the excited $^2P_{1/2}$ requires light at 369 nm. This wavelength is readily accessible by doubling light from a Ti:Sapphire laser or diode laser [4].

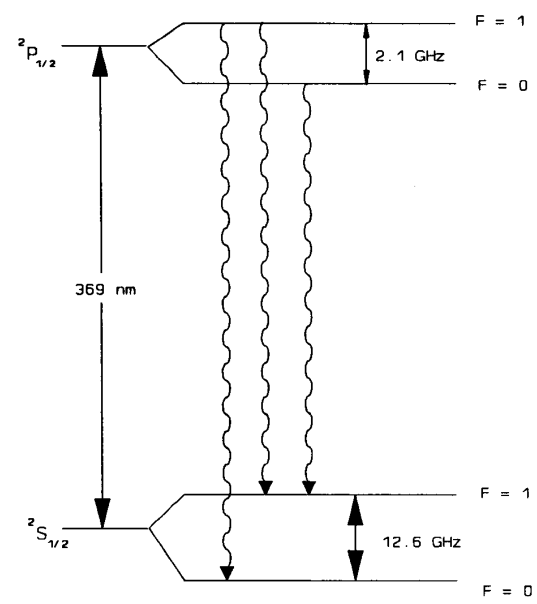

Figure 1: Hyperfine structure of the ground and first excited states in $^{171}Yb^+$.

We have designed a build-up ring cavity for the generation of 369 nm radiation using a 738 nm laser diode and a doubling crystal of lithium triborate (LBO) (Fig. 2). In order to overcome the low doubling efficiency associated with continuous-wave operation and milliwatt input powers, we have designed our cavity to take advantage of the increase in efficiency with tight focusing of the input beam. The two curved mirrors M3 and M4 will focus the fundamental beam to a waist of 25 μm in the doubling crystal. LBO is well-suited to this application due to its large acceptance angle, which allows tight focusing. The custom antireflection

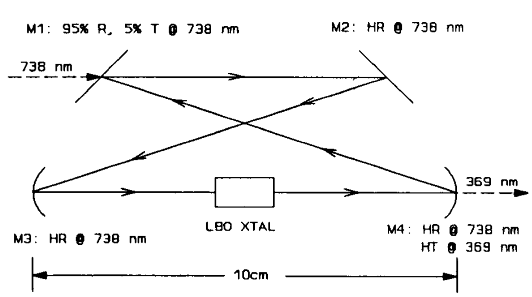

Figure 2: Design of optical buildup cavity for generation of 369 nm light necessary to reach the first excited electronic energy level in Yb^+.

coatings on the mirrors and crystal are expected to allow a buildup factor of approximately 15; therefore, a diode laser with output power of only 5 mW will provide 75 mW to the doubling crystal. With these considerations, we expect greater than 0.5% conversion efficiency, which will produce a minimum of 25 μW of 369 nm radiation with 5 mW of 738 nm input radiation.

Results of Spectroscopy Carried Out on Trapped Ytterbium Ions

Figure 3 shows a partial energy level diagram of singly ionised ytterbium. Using a linear rf/dc trap,

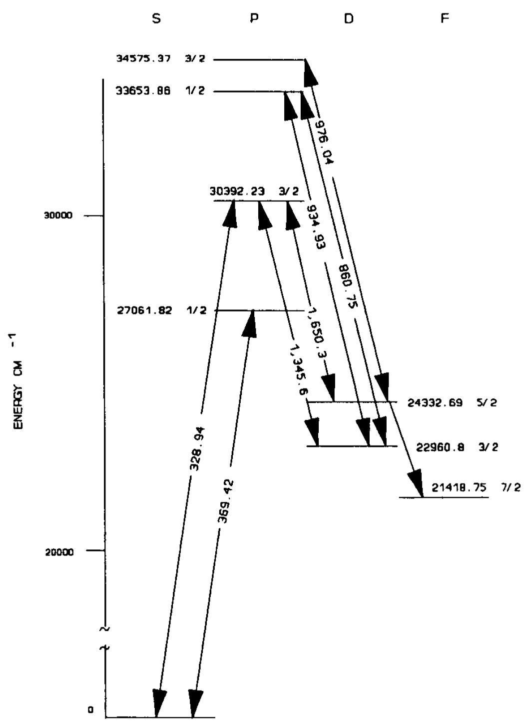

Figure 3: Simplified Yb^+ energy level diagram showing the eight levels involved in our experiment and numerical integrations.

which has been described previously [2], we have carried out extensive spectroscopy on naturally abundant ytterbium ions. We drove the $^2S_{1/2} \leftrightarrow {}^2P_{3/2}$ transition using 328.9 nm radiation generated by a Coherent 699-21 ring dye laser running with DCM Special laser dye and an intracavity lithium iodate (LIO) doubling crystal. Several milliwatts of uv power was generated this way, and a hollow cathode lamp was used to

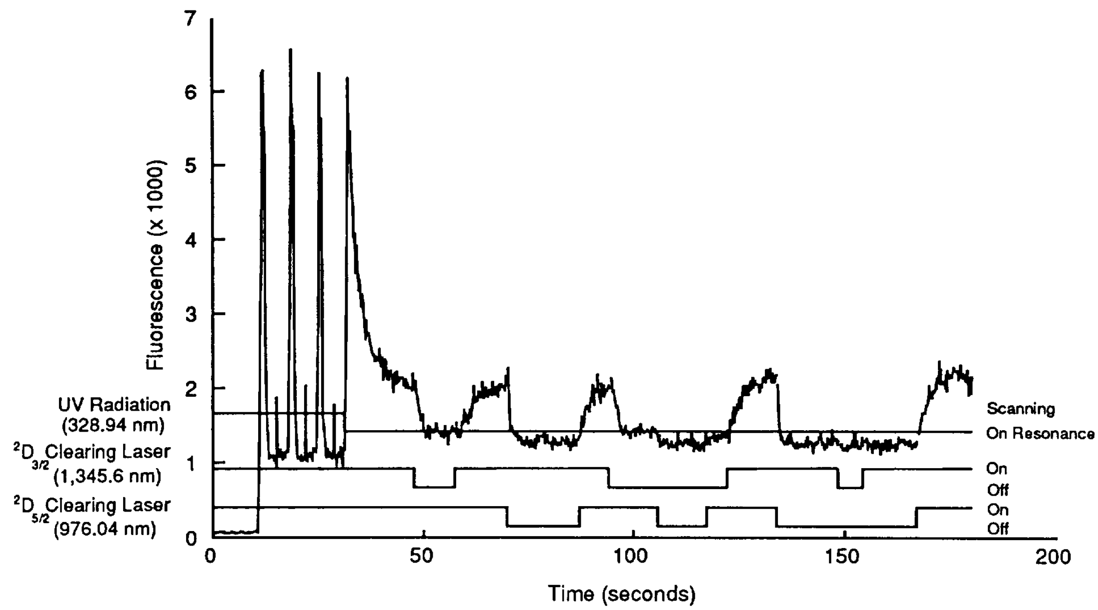

Figure 4: Ion fluorescence for various combinations of clearing lasers.

confirm resonance. We chose to excite the $^2P_{3/2}$ state, as opposed to the $^2P_{1/2}$ state, since it allowed direct decay to both the $^2D_{3/2}$ and $^2D_{5/2}$ states. This is important for the determination of the exact mechanism responsible for the population trapping first described by H. Lehmitz, et. al. [9].

Population trapping causes a loss of ion fluorescence by removing the ions from the cycling process between the ground state and the excited P state. Several mechanisms have been suggested by several different groups, all of which involve the eventual filling of a highly metastable $^2F_{7/2}$ state [3-9]. The $^2F_{7/2}$ state has a theoretical lifetime of 1533 days [13], while Lehmitz et. al have measured a dark period greater than 8 days [9].

In addition to pumping the $^2S_{1/2} \leftrightarrow {}^2P_{3/2}$ transition with 328.9 nm radiation we also drove the $4f^{14}(^1s)5d\,^2D_{3/2} \leftrightarrow 4f^{13}(^2F_{7/2})5d6s(^3D)^3[3/2]_{1/2}$, $4f^{14}(^1s)5d\,^2D_{5/2} \leftrightarrow 4f^{13}(^2F_{7/2})5d6s(^1D)^1[3/2]_{3/2}$, $4f^{14}(^1s)5d\,^2D_{3/2} \leftrightarrow 4f^{13}(^2F_{7/2})5d6s(^1D)^1[3/2]_{3/2}$, and $4f^{14}(^1s)5d\,^2D_{3/2} \leftrightarrow 4f^{14}(^1S)6p\,^2P_{3/2}$ transitions using 935 nm, 976 nm, 860 nm, and 1,345 nm radiation respectively. The 935 nm and 976 nm lasers are the best candidates for depopulating the $^2D_{3/2}$ and the $^2D_{5/2}$ levels since these are available semiconductor lasers. Semiconductor lasers at 860 nm are also readily available but could cause coherent population trapping problems when used with the 976 nm laser, as this would effectively connect the $^2D_{3/2}$ and the $^2D_{5/2}$ states. A similar problem exists between the 1,345 nm laser and the 329 nm laser since both these lasers drive transitions to the $^2P_{3/2}$ state.

Figure 4 shows the effect of simultaneous laser pumping with 328.9 nm, 976 nm, and 1,345 nm lasers. The 976 nm radiation was generated with a Spectra Physics 3900S Ti:Sapphire laser with output power of 300 mW in a 30 GHz linewidth. The 1,345 nm laser was a hand-selected Ortel LW300-E01 InGaAsP diode laser. A single fiber carried light from both lasers into the trap. An important point to notice in Fig. 4 is the rapid return of fluorescence after cycling the D state clearing lasers off and then back on again, implying no long-term loss of ions to the $^2F_{7/2}$ state. We are currently investigating the source of discrepancy between these results and the results obtained by others [3-9]. Our experimental setup is more sensitive to any population trapping that might take place in the $^2F_{7/2}$ state, since we populate the $^2D_{5/2}$ state directly. This state decays to the $^2F_{7/2}$ with a decay time of 6.3 msec or to the ground state with a decay time of 28.4 msec, according to the theoretical calculations of Fawcett and Wilson [13].

Figure 5 shows recent work using broadband semiconductor lasers at 935 nm and 976 nm fabricated by the Micro Devices Laboratory at JPL. Research in progress compares these four experimental

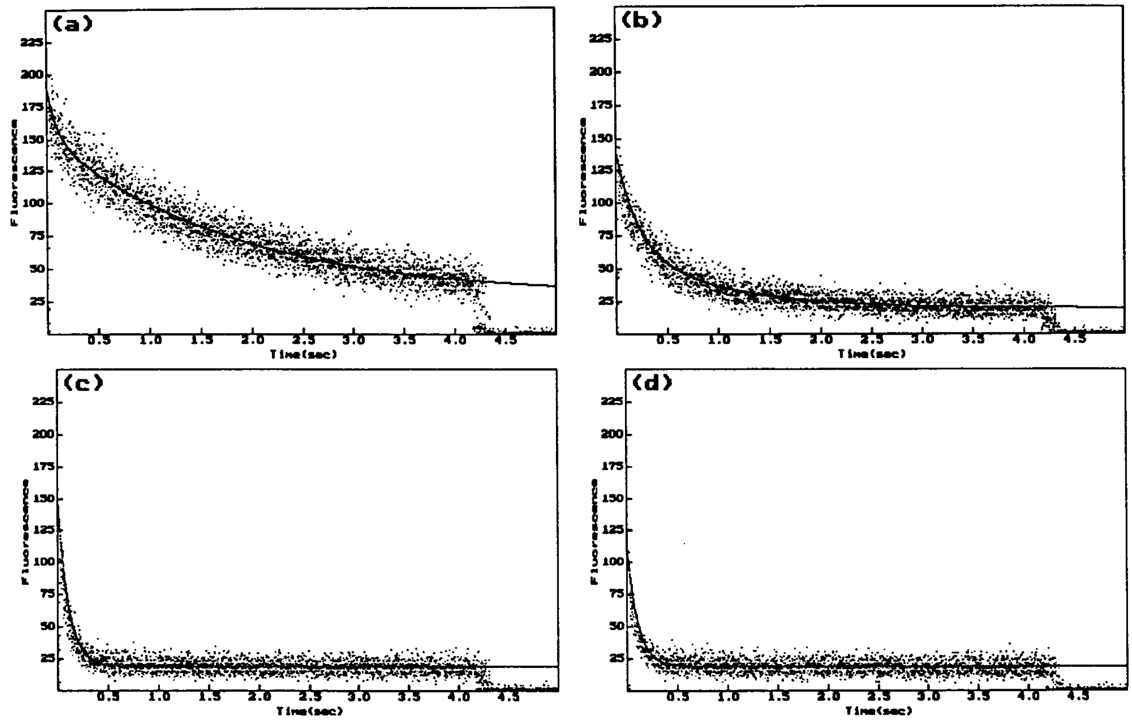

Figure 5: Experimental fluorescence decay curves under various laser excitations and best fits to the data. (a) 329 nm laser power ~ 100μW; 935 nm laser power ~ 1mW; 976 nm laser power ~ 2 mW; fluorescence=$121e^{-t/1769ms} + 28e^{-t/102ms} + 30$. (b) 329 nm laser power ~ 100μW; 935 nm laser power off; 976 nm laser power ~ 2 mW; fluorescence=$49e^{-t/899ms} + 61e^{-t/204ms} + 20$. (c) 329 nm laser power ~ 100μW; 935 nm laser power ~ 1mW; 976 nm laser power off; fluorescence=$103e^{-t/106ms} + 19$. (d) 329 nm laser power ~ 100μW; 935 nm laser power off; 976 nm laser power off; fluorescence=$74e^{-t/105ms} + 19$.

fluorescence decay curves with the P-state level populations obtained by numerically integrating the rate equations for the eight levels involved on a Cray supercomputer. The Einstein A and B coefficients for the various transitions are derived using the oscillator strengths quoted in Fawcett and Wilson [13]. This integration yields a longer decay time in the configuration of Fig. 5(b) than with both clearing lasers on as in Fig. 5(a), in conspicuous disagreement with the experimental results. The source of this discrepancy is presently under investigation.

Summary

We have pursued the development of a trapped ion standard based on singly-ionized ytterbium isotope 171. The choice of this ion is compatible with the use of semiconductor and solid- state lasers for optical pumping. We have demonstrated laser excitation of various levels of ytterbium ions trapped in a hybrid rf/dc linear trap using such lasers. Because there is considerable uncertainty associated with the role of low-lying metastable states of the ytterbium ion in population trapping, we have carried out spectroscopic investigations addressing this issue.

In the course of our experiments we have demonstrated the use of semiconductor lasers and fiber optics with trapped ytterbium ions. This is a crucial step in the development of small, reliable frequency standards for spacecraft deployment in support of various radio science investigations.

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