LASERS FOR A TRAPPED Hg^+ OPTICAL FREQUENCY STANDARD

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Abstract

We have demonstrated a frequency source at 563 nm with an approximately 6 Hz linewidth for use in an optical frequency standard based on trapped and cooled $^{199}Hg^+$ ions. Additionally, we are developing solid state laser replacements for gas and dye lasers presently used for driving 194 nm and 282 nm $^{199}Hg^+$ transitions.

Introduction

We have recently demonstrated an accurate microwave frequency standard using trapped and cooled $^{199}Hg^+$ ions [1]. We should achieve significant gains in statistical precision, and likely in accuracy, for an optical frequency standard that interrogates an ultraviolet transition in Hg^+ with a frequency of over 25 000 times the 40.5 GHz transition of the microwave frequency standard.

Figure 1 shows the $^{199}Hg^+$ electric dipole transitions at 194 nm used for laser cooling and the electric quadrupole transition at 282 nm that is the reference for the optical frequency standard. We generate this ultraviolet radiation using second-harmonic generation (SHG) and sum-frequency mixing (SFM) starting from Ar^+ lasers and a dye laser.

Recent advances in solid state lasers have made possible optical sources at these wavelengths with lower initial costs and operating costs, higher reliability and efficiency, and lower intrinsic noise than for Ar^+ and dye lasers. Consequently, we are developing solid state replacements for our present laser systems.

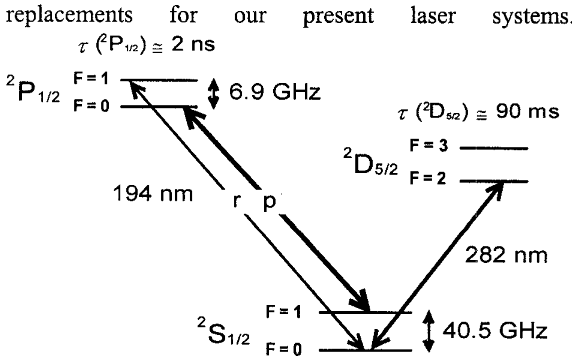

Figure 1: Energy level diagram of $^{199}Hg^+$. We cool the ions using the $^2S_{1/2} \rightarrow {}^2P_{1/2}$ transitions at 194 nm. Because the $^2P_{1/2}$, F=0 $\rightarrow {}^2S_{1/2}$, F=0 transition is forbidden, transition *p* is nearly a cycling transition. A second laser on transition *r* repumps atoms left in $^2S_{1/2}$, F=0 after off-resonant excitation to $^2P_{1/2}$, F=1.

Optical Frequency Standard

In order to observe narrow resonances, the driving source must have a frequency width comparable to or narrower than the transition linewidth. Consequently, one of the major steps toward the development of the optical frequency standard is the construction of an optical local oscillator with sufficient spectral purity.

The central component of this optical local oscillator is a high finesse (>50 000) Fabry-Perot cavity [2]. The separation of the cavity mirrors is set by optically contacting the mirrors to the ends of a hollow cylinder made from a low thermal expansion material. The mirror substrates are made of the same material as the cylinder.

The cavity is supported inside an evacuated chamber by two thin wires. Keeping the cavity under vacuum serves the dual purpose of avoiding pressure shifts of the cavity resonance and thermally insulating it from the environment. The temperature of the vacuum chamber is held near the point of zero coefficient of expansion for the cavity material.

We protect the cavity from seismic noise by mounting it on a passively isolated optical table. The table is suspended by strands of surgical tubing about 3 m long. The fundamental vibrational mode of the suspension has a frequency of ≈0.3 Hz, so the isolation from floor noise is ≈34 dB at 3 Hz (some viscous damping is used). To prevent the coupling of acoustic noise into the cavity, we enclose the optical table in a wooden box lined internally with lead foam [3].

We use a dye laser running at 563 nm as the optical source that is locked to the reference cavity. (The light is frequency doubled to 282 nm in a crystal close to the Hg^+ trap.) An intracavity electro-optic modulator (EOM) in the dye laser provides high frequency correction of laser frequency noise. A piezoelectric transducer (PZT) under one of the dye laser cavity mirrors eliminates long term frequency drifts between the dye laser and the cavity. An acousto-optic modulator (AOM) mounted on the isolation table provides intermediate frequency corrections.

Active control of the rf power driving the AOM stabilizes the output power from the cavity to ≈0.1%. The intracavity light causes heating of the mirror coatings, which shifts the cavity resonance. Controlling the optical power in the cavity stabilizes this power shift.

To allow measurement of the cavity's short-term stability without referencing to Hg^+, we constructed a second cavity system similar to that described above.

Figure 2 shows the spectrum of the beat note between two laser beams stabilized to the two cavities. The width of the spectrum at its half-power point is 8 Hz. If the frequency noise spectra of both sources are similar, then each source has a frequency width of less than 6 Hz at 563 nm, corresponding to a fractional linewidth of only 1.1×10^{-14}. This is roughly four times better than previous results with only one cavity well isolated from vibrations [2]. We think that this is the narrowest fractional frequency spectrum recorded in the optical regime.

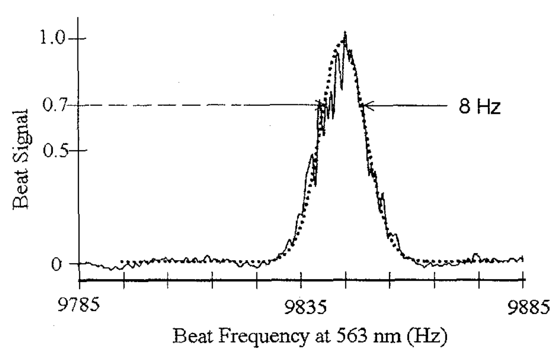

Figure 2: Amplitude spectrum of the beat note between two laser beams stabilized to two independent cavities. The dashed line shows the -3 dB level. The averaging time is 80 s. A nearly uniform relative cavity drift of ≈2 Hz/s is suppressed by mixing the beat note with a swept synthesizer.

Solid State Lasers

Nd:FAP laser

For the 282 nm light source, we plan to replace the dye laser and its multiline Ar^+ pump laser with a Nd:FAP laser [4]. Nd:FAP has a lasing transition at 1.126 µm, which when quadrupled covers the Hg^+ transition at 282 nm. The major difficulty in designing this laser is that Nd:FAP has a much stronger transition nearby at 1.063 µm [5], which must be suppressed by the laser optics.

With 680 mW of diode pump light at 808 nm, the Nd:FAP output power is about 90 mW at 1.126 µm. Frequency doubling in $KNbO_3$ gives about 5 mW at 563 nm, which is sufficient optical power for our purposes.

Yb:YAG laser

Currently, the 194 nm cooling light is generated using a single-mode Ar^+ laser at 515 nm that is frequency doubled in beta-barium borate (BBO) to 257 nm and is then sum-frequency mixed in BBO with a diode source at 792 nm to produce light at 194 nm [6]. We plan to replace the Ar^+ laser with a Yb:YAG laser at 1.03 µm [7]. With 3 W of diode pump power at 941 nm, the Yb:YAG output power is 1.2 W at 1.03 µm. We have doubled this in $KNbO_3$ to obtain over 400 mW at 515 nm, which should be sufficient power to replace the Ar^+ laser. At high optical powers, the frequency-doubling conversion efficiency is limited by losses from blue-light-induced infrared absorption [8]. We anticipate achieving a better conversion efficiency by doubling with lithium tetraborate (LBO) instead.

Summary

We have demonstrated an optical local oscillator for use with a Hg^+ optical frequency standard at 282 nm. The frequency source has a linewidth of about 6 Hz at 563 nm, corresponding to a fractional linewidth of 1.1×10^{-14}. We have also nearly completed work on solid state laser replacements for gas and dye lasers presently used in the trapped Hg^+ work. This work is supported by ONR.

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