Stable Laser System for Probing the Clock Transition at 578 nm in Neutral Ytterbium

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***Abstract*—We describe a new laser system we have developed to probe the ultra-narrow $^1S_0 \leftrightarrow {}^3P_0$ clock transition at 578 nm in neutral ytterbium. The yellow light is produced by sum frequency generation in a periodically poled waveguide. With approximately 100 mW each from a fiber laser and Nd:YAG laser, we produce 10 mW of visible light. Stabilization of the laser to a resonance of a high finesse, environmentally isolated cavity has enabled resolution of spectroscopic features as narrow as 5 Hz.**

I. INTRODUCTION

We have recently developed a new laser system for probing the $^1S_0 \leftrightarrow {}^3P_0$ transition at 578 nm in neutral ytterbium. This nearly forbidden transition has shown considerable promise as a reference for an optical atomic clock, especially when used with atoms confined to an optical lattice [1-3]. In this case the long interaction time provided by the lattice confinement of the atoms enables extremely high resolution spectroscopy of the clock transition. Indeed, we have resolved spectral features as narrow as 4 Hz (FWHM) with a stabilized dye laser [3]. In order to have a simpler, more robust probe laser, we have assembled a solid-state/fiber-based system that takes advantage of improved nonlinear optics capabilities. With a preliminary version of this laser, we have attained a FWHM linewidth of 5 Hz, with good prospects for still higher resolution. An improved version of this system should be able to support the projected performance levels of a lattice-based ytterbium optical clock: namely, an absolute fractional uncertainty well below 10^{-16}, with a fractional frequency instability well below 10^{-15} at 1 s.

II. SUM FREQUENCY APPARATUS

A. *Overview*

The sum frequency apparatus consists of three main parts: two infrared lasers (at 1.03 μm and 1.319 μm) and a non-linear waveguide that has been periodically poled with the appropriate period for sum frequency generation (see Fig. 1) [4]. We need to use two infrared sources because there is no available source at 1.156 μm with sufficient power for frequency doubling. The two infrared sources are combined with a dichroic beamsplitter and then mode-matched into a fiber that is coupled to the waveguide. The yellow output is separated from residual infrared light by a dichroic beamsplitter.

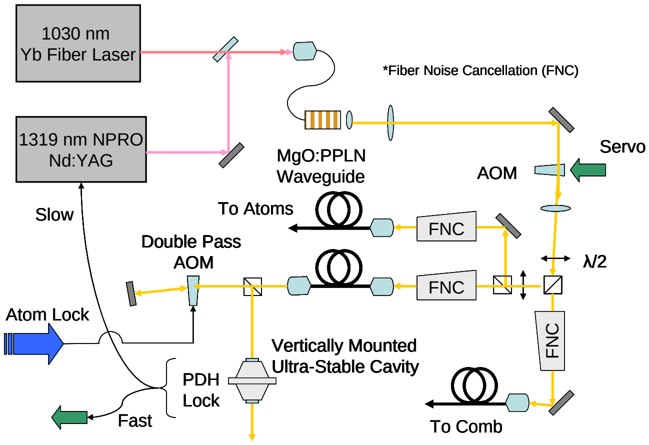

Figure 1. Schematic of the laser system used to probe the 578 nm clock transition in neutral Yb. The yellow light is produced through single-pass sum frequency generation in a periodically-poled non-linear waveguide. The frequency of the light is locked to a resonance of a high-finesse cavity through fast feedback to an acousto-optic modulator (AOM) and slow feedback to a PZT on the Nd:YAG laser.

B. *Infrared Lasers*

The 1.319 μm light is supplied by a commercial Nd:YAG source with an output power of 350 mW. Due to its intrinsically narrow linewidth and fast modulation capabilities, this laser is well suited for development of an ultrastable laser. In a preliminary evaluation of the Nd:YAG laser, we doubled its frequency so we could compare it to a stable red source at 659 nm. We measured the infrared laser linewidth to be ~ 2 kHz (over 1 s) and found we could lock its frequency tightly to that of the red laser with a loop bandwidth of 100 kHz. The 1.03 μm light comes from a commercial fiber-laser master oscillator whose output is amplified up to 1 W by a fiber amplifier. The fiber laser has a linewidth of ~10 kHz and two channels for controlling the laser frequency. The fast channel controls the voltage on a piezo-electric transducer (PZT) on

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the master fiber (bandwidth ~ 10 kHz), while the slow channel controls the fiber temperature (bandwith ~ 1 Hz).

C. Nonlinear optics with a periodically-poled waveguide

Our initial version of this laser system used a singly passed bulk Mg:PPLN (Mg doped periodically poled lithium niobate) crystal that was poled to optimize its efficiency for sum frequency generation for our wavelengths. While this worked fine, we have recently replaced the bulk crystal with a fiber-coupled waveguide, due to the enhanced sum frequency efficiency that results from the tight confinement of the light in the waveguide. The waveguide has a convenient phase-matching temperature of 60 °C, which we control by placing the waveguide in a simple oven. With the input light appropriately polarized, we find that we can generate 12 mW of 578 nm light with 100 mW of 1.03 μm light and 150 mW of 1.319 μm input levels. We achieve about 50 % coupling of the input light beams into the fiber, so the effective efficiency is actually ~ 450 % / W. This is about a factor of 100 higher than we achieved with the bulk crystal, so we are able to use about eight times less power with our fiber laser, which we will hope will greatly increase its reliability and lifetime.

III. STABILIZING THE LASER

While our demands for power at 578 nm are comparatively modest, our demands for laser stability are not. In order to resolve the hertz-wide spectra possible with the lattice-confined atoms, it is necessary to have an extremely stable probe laser. Ideally, the probe laser would have an instability of less than 1 Hz over time scales of tens of seconds. The free-running yellow light generated from the two infrared sources has a linewidth of 15-20 kHz, not a bad place to start, but far from where we need to be.

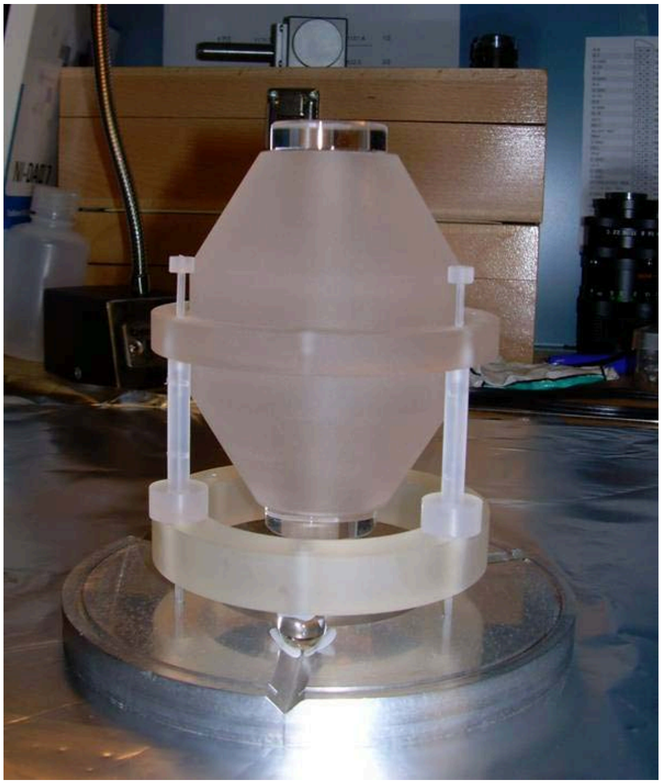

Figure 2. The optical cavity used for stabilization of the yellow light. It is based on a design described in [5] that supports the cavity at its midpoint to minimize its sensitivity to vibrations.

To stabilize the laser frequency, we use a narrow resonance (~ 10 kHz) from a stable Fabry-Perot cavity. We have mounted the cylindrical cavity (held at its midpoint) in a vertical orientation [5] in an effort to minimize its sensitivity to external vibrations (see Fig. 2). The cavity is located inside an Al vacuum can, which rests on a breadboard that also contains optics used to generate the error signal used for locking. We placed the breadboard on an active vibration isolation platform, which is enclosed by a passive acoustic isolation chamber. With roughly 15 μW of light coupled to a TEM_{00} mode of the cavity, we lock the frequency of the yellow light with the Pound-Drever-Hall technique (modulation frequency = 22.6 MHz) [6]. We use two feedback channels in the lock – the fastest corrections are sent to an acousto-optic modulator, while slower corrections are sent to a PZT on the Nd:YAG laser. With a servo bandwidth of 600 kHz we are able to reduce the laser linewidth to 1 Hz on a several second time scale. Temperature control of the cavity's vacuum can has limited the laser's frequency drift to 0.5 Hz/s, which seems to be related to settling of the cavity (the drift has not changed sign in the 3 months since we mounted the cavity).

IV. MEASUREMENTS OF THE LASER PERFORMANCE

With the laser frequency locked to the resonance of the optical cavity lying nearest to the frequency of the Yb clock transition, we have evaluated the clock laser in several different ways. First, we sent some of the light through an

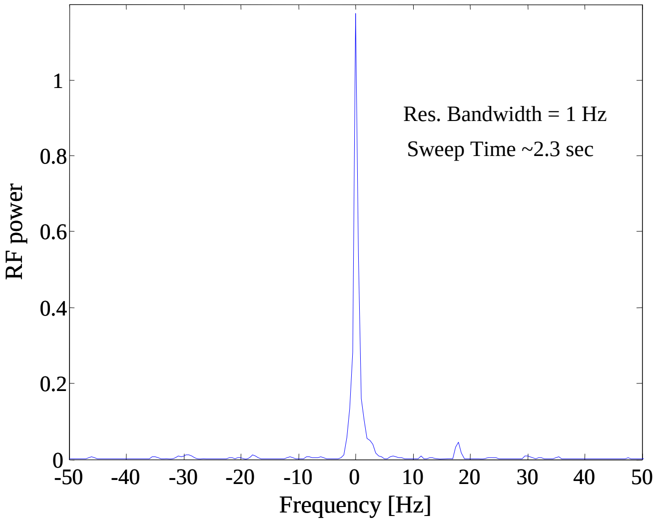

Figure 3. The beatnote between 578 nm light stabilized to the optical cavity and the nearest mode of a mode-locked fs-laser locked to a stable source near 1 μm. The FWHM of the carrier is less than 2 Hz.

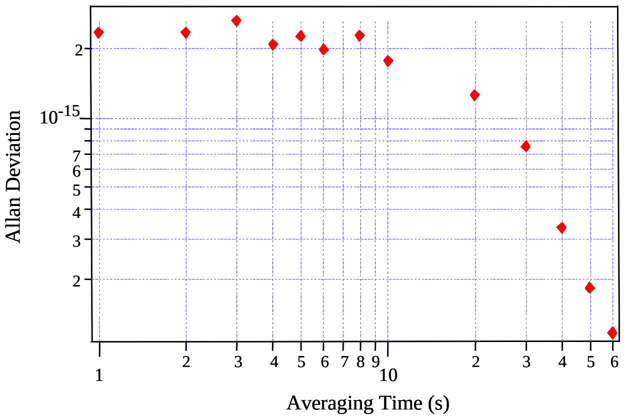

Figure 4. The Allan deviation for the beatnote shown in Fig. 3. The value of 2.2 x 10^{-15} at 1-2 s is consistent with the linewidth shown in Fig. 3. A linear frequency drift between the lasers was subtracted from the raw data.

optical fiber to a mode-locked femtosecond-laser frequency comb setup that enables comparisons between the clock laser and other stable frequency sources [7]. In order to measure the instability of the clock laser, it is necessary to cancel the noise written onto the light by the fiber itself. In Fig. 3 we show a trace from a spectrum analyzer of the effective beatnote mediated by the femtosecond-laser (with all fiber noise contributions cancelled) between the 578 nm light and light from a 1.068 μm source that is locked to an ultrastable cavity. Here we see a linewidth of slightly more than 1 Hz (partially resolution bandwidth limited) for a 2.3 s sweep. In Fig. 4 we show an Allan deviation of the normalized frequency fluctuations between the sources (a linear drift was removed from the frequency data before the Allan deviation was calculated). The value of 2.2 x 10^{-15} at 1 s is consistent with the spectrum in Fig. 3.

As a second test we have used this laser to probe the clock transition for a range of interaction times. When we probe atoms held in a 1-D optical lattice along the axis of tight confinement, motional effects are suppressed. In this case the spectral resolution is usually limited by the interaction time or the laser frequency noise. With this new probe laser we find that the spectra are Fourier limited until we reach interaction times of ~ 200 ms, at which time the laser frequency noise begins to contribute. Fig. 5 shows a spectrum with a FWHM of about 5 Hz, only slightly above the Fourier limit of 4.3 Hz. Since this spectrum was taken when the probe laser exhibited fluctuations about two times larger than those shown in Fig. 4, we expect that future investigations should resolve still narrower spectra.

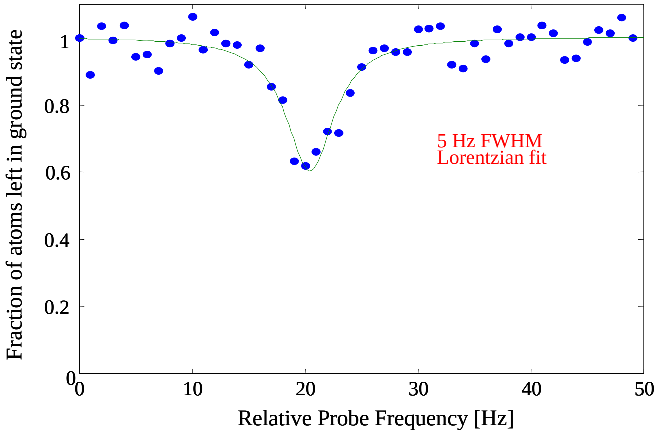

Figure 5. Spectrum taken of the Yb clock transition with the laser system described in this work. Atoms confined to an optical lattice tuned close to its magic wavelength [1] were excited by a single excitation pulse with a duration of 200 ms. The scan was taken without averaging – the data acquisition period was 500 ms per point.

V. FUTURE PROSPECTS

We have presented initial results with a laser system that we recently developed for probing the Yb clock transition. The present laser performance should be adequate for producing extremely high Q spectra for the lattice-confined Yb atoms, and should in principle be able to support an optical atomic clock with instability of 3 x 10^{-15} $\tau^{-1/2}$. Additionally, this new local oscillator should enable a detailed investigation of the absolute uncertainty of the Yb laser clock frequency at the 10^{-16} level or better. Already we have begun measurements of the lattice intensity and detuning effects on the clock transition and anticipate a full evaluation of the clock systematics over the coming months.

Ultimately, we hope to approach the calculated limits for the Yb clock instability, which would be below 10^{-16} $\tau^{-1/2}$ for a sample of 10^5 atoms and a line Q of 10^{14}. However, we would need to improve the laser stabilization by more than an order of magnitude to support this level. While we have not yet determined what presently limits the laser frequency stability, the noise level is not far above the thermal noise limit for the cavity [8]. In order to reduce the thermal noise limit, it will be necessary to modify the cavity by increasing its length, and using mirrors with a different substrate material and perhaps a different coating material as well. We also plan to compare the performance of active and passive vibration isolation platforms.

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