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ABSTRACT

Isotope selective optical excitation of atoms is important for experiments with neutral atoms, metrology, and work with trapped ions, including quantum information processing. Polarization-enhanced absorption spectroscopy is used to frequency stabilize a tunable external cavity laser diode system at 398.9 nm for isotope selective photoionization of neutral Yb atoms. This spectroscopy technique is used to measure isotope resolved dispersive features from transitions within a see-through configuration ytterbium hollow-cathode discharge lamp. This Doppler-free dichroic polarization spectroscopy is realized by retro-reflecting a laser beam through the discharge and analyzing the polarization dependent absorption with balanced detection. The spectroscopy signal is recovered using lock-in detection of frequency modulation induced by current modulation of the external cavity laser diode. Here, we show an order of magnitude improvement in the long-term stability using polarization-enhanced absorption spectroscopy of Yb compared to polarization spectroscopy.

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I. INTRODUCTION

The 398.9 nm $^1S_0 \leftrightarrow ^1P_1$ transition is commonly used in both Yb and Yb⁺ atomic physics experiments due to its large dipole moment and accessibility with low-cost laser diodes. For neutral Yb, this transition allows for faster cooling and a broader velocity capture range of atoms than the narrower 555.8 nm $^1S_0 \leftrightarrow ^3P_1$ transition, eliminating the need for a Zeeman slower,¹ while still being suitable for sub-Doppler cooling.² For generating Yb⁺ ions, the 398.9 nm transition provides a well-resolved isotope selective excitation step in the ionization process, which is frequently completed by continuum ionization by the Yb⁺ UV cooling laser at 369.5 nm. This approach is more economical and accessible than using an isotope-enriched Yb source combined with non-isotope selective electron impact ionization.³

Frequency-stable lasers, tunable to within a few MHz of an atomic resonance, are now a standard tool for precision atomic

physics experiments.^{4–8} Common approaches to frequency stabilize a CW laser include interfering it with a stabilized optical frequency comb^{4,9} as well as using a Fabry–Pérot transfer cavity^{7,8,10,11} or commercial Fizeau-interferometer-based wavemeter^{12,13} to transfer the frequency stability from one laser wavelength to another. All of these options require an existing stable frequency reference, which can result in a greater cost, greater complexity, or potentially lower robustness over directly stabilizing the laser frequency to the desired atomic frequency standard. As an alternative vacuum, isolated Fabry–Pérot cavities with drifts of 80 Hz/s¹⁴ and –1.02 MHz/day¹⁵ have been shown to be sufficient for atomic physics experiments without the need for regular stabilization to an absolute frequency standard.

Numerous spectroscopy techniques have been reported,¹⁶ primarily using atomic or molecular vapor cells.¹⁷ Traditional vapor cells are not suitable for low vapor pressure/high boiling point elements including ytterbium. At room temperature, Yb has a vapor

pressure 11 orders of magnitude lower than cesium or rubidium. Increasing the temperature to produce comparable pressures results in Yb reacting chemically with the glass windows of a vapor cell. Efforts have been made to design and build vapor cells for elements including strontium and ytterbium;^{18,19} however, there are no commercially available options. A reliable and cost-effective alternative to stabilize a UV laser is using atoms produced in the discharge of a hollow-cathode lamp (HCL). First demonstrated in 1970,²⁰ laser stabilization to a discharge has been extended to various atomic species, including neutral ytterbium,²¹ erbium,^{22–24} dysprosium,²⁵ chromium,²⁶ and strontium.²⁷ Several spectroscopy techniques using Yb have been reported in an atomic oven²⁸ or a discharge lamp including modulation transfer spectroscopy (MTS),²⁹ which uses non-linear four-wave mixing as well as dichroic atomic vapor laser locking (DAVLL).^{21,30} In addition, other experiments with hollow cathode lamps have utilized polarization spectroscopy (PS) to measure sub-Doppler features for both neutral and ionized Yb, which are stable with respect to frequency.^{31,32} The ability to swap between probing dichroism and laser-induced birefringence in a discharge by changing the analysis optics has been reported.³³

Here, we demonstrate the use of polarization-enhanced absorption spectroscopy (POLEAS)³⁴ to probe the dichroism of a Yb transition. When compared to PS, POLEAS has a locking frequency stability at least ten times less sensitive to polarization drift, aided by the different analysis optics while still providing a larger signal-to-noise ratio (SNR) than Doppler-free saturation absorption spectroscopy (D-F SAS).^{35,36} POLEAS is also cheaper than MTS for this near UV transition, as it can be achieved without extra components for creating sidebands on a sub-400 nm laser beam. This is the first time this type of spectroscopy has been used on ytterbium in a discharge lamp and swapping from PS to POLEAS requires minimal changes to a spectroscopy system.

II. PRINCIPLE OF THE TECHNIQUE

A key aspect of many high precision spectroscopy techniques is the ability to produce well-resolved, stable dispersive features suitable for incorporation into a frequency stabilization servo loop. Many of these spectroscopy techniques modulate the laser light, which results in a change of the response of the atomic system, such that the obtained signal from probing the sample can be passed through a lock-in amplifier to obtain a sharp and stable error signal feature.

In its most elementary form, D-F SAS comprises a pump beam and a counter-propagating probe beam. The nonlinear interaction between the counter-propagating beams enables the tighter constraints in this spectroscopy technique, restricting the atom interaction with both beams simultaneously to a particular velocity class, resulting in a Doppler-free spectroscopy signal. The probe beam changes properties (amplitude and polarization) as it passes through a sample and gets sent to an analysis setup. The presence of the on-resonant pump beam saturates the transition and reduces the change in probe beam properties. The pump beam modulation is sent to a lock-in amplifier as a reference signal and is mixed with the signal obtained from the probe beam after the analysis setup. Due to the beams being counter propagating, assuming perfect

overlap, the end signal is free from the heterogeneous first order Doppler broadening.

Figure 1 shows a generic setup for both PS and POLEAS along with the expected output signals after lock-in detection. The setup for PS and POLEAS is similar in pump and probe beam polarizations; however, they differ in the analysis optics. A circularly polarized pump beam is sent through the sample (for convention, let us call this σ^R). The counter propagating probe light is linearly polarized, which is also an equal superposition of σ^R and σ^L . The pump beam saturates the transition for the counter propagating σ^L light. This uses the same counter-propagating beam technique as D-F SAS, and thus, the Doppler broadened spread in the resonant frequency of the transition can be ignored. For a two-level atomic transition, the probe light experiences a change in its properties explained by the complex absorption coefficient, which, when broken into its real and imaginary parts, is³⁷

$$\text{Re}(\alpha) = \alpha_0 \frac{\gamma^2}{\gamma'^2 + (\omega_0 - \omega)^2} \quad (1)$$

and

$$\text{Im}(\alpha) = -\alpha_0 \frac{\gamma(\omega_0 - \omega)}{\gamma'^2 + (\omega_0 - \omega)^2}, \quad (2)$$

where

$$\gamma' = \gamma\sqrt{1 + s_0} \quad (3)$$

and

$$s_0 = \frac{I}{I_{\text{sat}}} = \frac{3I\lambda^3\tau}{\pi\hbar c}. \quad (4)$$

FIG. 1. The top optical setup probes laser-induced birefringence and is commonly referred to as PS. The bottom optical setup probes dichroism and is referred to as POLEAS. The only difference between these two schematics is the wave plate used before the analysis optics, shown in red and blue. The right of each optical setup is a theoretical example of a spectroscopy feature, calculated from Eqs. (1) and (2) with $s_0 = 0$ for feature clarity. For PS, $\text{Im}(\alpha)/\alpha_0$ is plotted. For POLEAS, $\text{Re}(\alpha)/\alpha_0$ is plotted. HCL—hollow-cathode lamp, PBS—polarizing beam splitter, ND—variable neutral density filter, H—horizontal polarization, and V—vertical polarization.

Here, α_0 is the linear resonant absorption coefficient ($s_0 = 0$), s_0 is the dimensionless on-resonance saturation parameter, ω is the laser frequency, ω_0 is the transition resonant frequency, γ is the natural transition linewidth, and γ' is the power-broadened linewidth. Equations (1) and (2) are similar to the Kramers–Kronig dispersion relations obtained when looking at the real and imaginary parts of the complex refractive index.¹⁷ The analysis optics are set up such that, for PS, the real part of the complex absorption coefficient is suppressed and, for POLEAS, the imaginary part is suppressed. The reason for this is as follows.

For PS, without an atomic sample, the probe beam is set to a linear polarization such that equal amounts of both σ^R and σ^L light go to both detectors for analysis. In this case, the polarization controlling $\lambda/2$ wave plate in the probe arm can be before or after the sample. When probing the sample, the change in absorption is fed into both detectors equally and is filtered out when taking the difference between detectors. However, the σ^R light and σ^L light experience circular dichroism proportional to the difference in absorption coefficients $\Delta\alpha = \text{Im}(\alpha)^{+,L} - \text{Im}(\alpha)^{-,R}$. This, as well as the change in amplitude between the σ^R and σ^L light, changes the probe beam polarization after the lamp to be slightly elliptical. For a frequency blue shifted from resonance, this ellipticity sends more light toward one detector, and when the frequency is red shifted from resonance, more light is sent to the other detector. This produces the dispersive spectroscopy locking signal. This setup is highly sensitive to polarization fluctuations of the probe beam and any fluctuation of the $\lambda/2$ wave plate from temperature, as the resulting changes to the spectroscopy signal appear similar to that caused by changes in the laser frequency.

For POLEAS, without an atomic sample, the probe beam is again set to a linear polarization such that equal amounts of both σ^R and σ^L light go to both detectors. However, by placing a $\lambda/4$ wave plate after the sample, all of the σ^R light can be sent to one detector, while all of the σ^L light is sent to the other detector. The difference in the amount of light at each detector is determined by the complex absorption coefficients for the σ^R and σ^L light through the sample, where $\text{Re}(\alpha)$ dominates in the end feature. The effects from $\text{Im}(\alpha)$ are suppressed as this spectroscopy is first order insensitive to polarization fluctuations of the probe beam from induced circular dichroism, or from temperature shifts of the $\lambda/4$ wave plate. In the compressed form of POLEAS, the probe beam is a retroreflected portion of the pump beam. The Doppler-free absorption profile obtained from this spectroscopy is then converted into a suitable locking signal through frequency modulation of the laser.^{38–40}

III. YTTERBIUM SPECTROSCOPY

Ytterbium has a relatively straightforward lower energy level structure with optically accessible transitions that are suitable for laser cooling in both neutral and ionized Yb^+ atomic physics experiments. Ytterbium has seven naturally occurring isotopes with atomic mass units and abundances shown in Table I. Here, we considered the two most abundant isotopes (^{174}Yb , ^{172}Yb) as well as ^{171}Yb that is frequently used for quantum information processing (QIP).

^{174}Yb and ^{172}Yb have a simpler energy level structure compared to ^{171}Yb because the ground-state nuclear spin is zero for even

TABLE I. Yb isotopes and their naturally occurring abundances.

Yb isotope	Precise atomic mass ⁴¹	Abundance (%) ^{42,43}
168		0.1232(4)
170	169.934 767 241(18)	2.982(6)
171	170.936 331 514(19)	14.086(20)
172	171.936 386 655(18)	21.686(19)
173	172.938 216 213(18)	16.103(9)
174	173.938 867 539(18)	32.025(12)
176	175.942 574 702(22)	12.995(1.3)

isotopes and 1/2 for ^{171}Yb . This nuclear spin of 1/2, which interacts with the electron spin, splits the energy levels and results in a hyperfine structure in ^{171}Yb (see Fig. 2). For $^{171}\text{Yb}^+$, this hyperfine structure splitting of the ground state is 12.64 GHz,^{44,45} which provides long lived microwave accessible states for QIP.^{47,48} This hyperfine splitting also provides a single $F = 0$ ground state, which is ideal for optical ion clocks used in metrology.⁴⁹ The simpler energy level structure in the even isotopes makes them useful for studying fundamental physics problems, such as observing the shadow of a single ion⁵⁰ or sensing sub-attoneutron forces in three dimensions,⁵¹ with minimal parameters and relaxes the requirements on needed equipment. This also makes them useful when setting up a new experiment for QIP applications.⁵²

Table II and Fig. 3 provide detailed information on the $^1S_0 \leftrightarrow ^1P_1$ transition around 398.9 nm for the different isotopes with respect to the transition frequency in ^{174}Yb . Table II lists the isotope specific shift in the resonant frequency, and in Fig. 3, we estimate the potential isotopic purity of ion formation from a natural abundance source based on the excitation probabilities as a function of laser detuning.

The ionization purity f_i (Fig. 3) is calculated for a given laser frequency ω from the relative scattering rate for a particular isotope Γ_i vs the total scattering rate from a natural abundance distribution,

$$f_i(\omega) = \frac{\Gamma_i(\omega)}{\sum_n \Gamma_n(\omega)}. \quad (5)$$

FIG. 2. Relevant energy levels for the Yb isotopes producing prominent spectroscopy features suitable for laser stabilization. Excited state lifetime $\tau = 5.51$ ns calculated from Ref. 54. The transitions shown with arrows are saturated via the pump beam, dependent on the magnetic field direction. A more complete energy level structure can be found from Ref. 31. For ^{171}Yb , the 1S_0 ground-state m_F levels are split by the nuclear spin, while the excited 1P_1 state m_F levels are split by the electronic and nuclear magnetic dipole interactions.

TABLE II. Yb isotopes and their 398.9 nm $^1S_0 \leftrightarrow ^1P_1$ transition frequency shifts.⁴⁶

Yb isotope	Hyperfine level	Isotope shift (MHz) ^a
168		1887.400(50)
170		1192.393(66)
171	(F' = 1/2)	1153.696(61)
171	(F' = 3/2)	832.436(50)
173	(F' = 7/2)	587.986(56)
172		533.309(53)
173	(F' = 3/2)	515.975(200)
174		0
173	(F' = 5/2)	−253.418(50)
176		−509.310(50)

^aRelative to ^{174}Yb . **FIG. 3.** Isotope ionization purity rates of neutral Yb on the 398.9 nm $^1S_0 \leftrightarrow ^1P_1$ transition for a natural abundance source as a function of detuning. The plot is for a collimated laser beam perpendicular to a dilute collimated atomic beam (zero Doppler broadening), in the low laser intensity limit with no optical pumping. Detunings are with respect to the transition frequency in ^{174}Yb . Note that for ^{171}Yb , exciting the F = 3/2 transition provides the largest probability of only exciting that isotope.

For isotopes 171 and 173 with nuclear spin $I \neq 0$, the scattering rate is the sum across all transitions with a weighting factor h_j based on the spin multiplicity,

$$\Gamma_i(\omega) = \sum_j h_j \frac{\gamma_{s0}/2}{1 + s_0 + 4(\omega_j - \omega)^2 \gamma^{-2}}. \quad (6)$$

IV. EXPERIMENTAL METHODS AND RESULTS

Three setups were tested for obtaining Yb spectroscopy. The simplest one utilized an in-house assembled external-cavity diode laser (ECDL), shown in Fig. 4. In this setup, the 398.9 nm laser system consists of an ECDL on a temperature stabilized base. The UV laser diode (Nichia Corporation LD-0397-0030-1) has a free running wavelength of 397.9 nm, tuned to 398.9 nm by optical feedback from a Littrow configuration 3600 groove/mm holographic grating

(Thorlabs GH13-36U). The diode is driven with a combination of direct current and current modulation. The direct current ranges from 41.41 mA to 43.10 mA for day to day use. This provides a total ECDL output power of 11 mW after the grating. The modulation depth is estimated as 1.25 MHz/ μA from measurements using a wavemeter. A peak-to-peak modulation depth of 25 MHz was used at a modulation rate of 50 kHz. The beam out of the laser diode is collimated using an asphere (Thorlabs C671TME-A), providing an elliptical beam with Gaussian $1/e^2$ diameters of 1.89(1) mm in the horizontal direction and 0.51(1) mm in the vertical direction. To prevent unwanted back reflections into the diode, modulating the laser frequency or amplitude, we use an optical isolator (Conoptics 711C-1) with 80% transmission in the forward direction and 37 dB isolation in the reverse direction. The 9 mW beam out of the isolator gets split on a polarizing beam splitter (PBS) cube where 2 mW of light is sent to an ion-trap experiment via a polarization maintaining optical fiber. The remaining 7 mW of light is turned circularly polarized, using a $\lambda/4$ wave plate, and sent through a DC hollow-cathode lamp backfilled with Ne buffer gas (Hamamatsu L2783-70NE-Yb) operating at a supply current of 1.2 mA and a voltage of 140 V. The choice of buffer gas species is not critical for neutral atom spectroscopy; however, it does have a substantial impact on the in-lamp ion population.³⁰ The estimated pressure broadening from neon gas colliding with neutral ytterbium is not present in the literature and was estimated as 7 MHz/Torr at room temperature. This value was calculated from a hard sphere model for collisions and using the covalent radii of the two atoms.

The complete drive circuitry for this lamp is shown in Fig. 4, with the DC power supply operating in the current limited mode. The lamp is housed in a die-cast aluminum container with no

FIG. 4. Optical setup for spectroscopy using the in-house external-cavity diode laser (ECDL). The ECDL provides a total output power of 9 mW after the optical isolator. Part of the light from the ECDL is picked off before the spectroscopy and fiber coupled to a 2D RF Paul trap (trap 1). The spectroscopy is realized in a hollow-cathode lamp (HCL), and the absorption signal is recorded on a differential photodiode (BPD). After the HCL, the beam passes through a PBS where the reflected component is sent out of the setup and sent to a 3D RF Paul trap (trap 2). Also shown are the electronics to generate the error signal, which is fed back into the laser, and the electronic circuit used for controlling the HCL. The electric potential between the HCL anode and cathode results in neutral, excited, and ionized Ne buffer gas atoms. Ne⁺ ions bombard the Yb cathode, sputtering neutral Yb through the lamp.⁵³ The second optical setup replaced the ECDL with a Moglabs laser system and fiber coupled 3.54(1) mW into the setup before the optical isolator. The third optical setup replaced the Moglabs laser with an M Squared SolisTiS plus ECD-X laser system and fiber coupled 8.26(1) mW into the setup before the optical isolator.

external magnetic fields applied and designed for optical access at both sides with windows at a 10° angle to deflect back reflections. It comprises a ring cathode of length 19 mm and bore diameter 3 mm. The collimated beam exits the hollow cathode lamp and passes through a PBS, where the reflected portion of the beam is sent to a second ion-trap experiment. The transmitted portion of the beam is then retroreflected through the discharge, and $\lambda/4$ wave plate, before a fraction of that light is picked off using a glass blank and sent for analysis. This light is split on a PBS and sent to a balanced pair of photodiodes. In order to precisely balance the photocurrents, we use a variable neutral density filter (ND) to balance the optical power. The difference in the detector's measured current is amplified, providing an absorption signal on a flat background. A Newport 2107-FS-M balanced photoreceiver was used for spectroscopy and locking stability measurements. It has a measured conversion gain of 88.3(5) mV/ μ W and a bandwidth of 10 MHz.

To further amplify the POLEAS signal, as well as to turn it into a zero-crossing locking signal by taking its derivative, we frequency modulated the laser through its drive current. The laser was modulated at a frequency of 20 kHz, with the modulation depth optimized for the largest signal-to-noise ratio without reducing feature details. Any change in the laser power from drive current modulation was filtered out of the spectroscopy signal through the balanced photodiodes. For lock-in detection, we used a Stanford Research Systems' SR510 lock-in amplifier, with a sensitivity of 1 mV/V and a post low-pass filter time of 0.1 s. In Fig. 5(c), the resulting signal out of the lock-in amplifier is shown. Changing the lamp current then changed the peak-to-peak height of the spectroscopy features. As described in Ref. 31 for the case of PS of Yb in a discharge, the size (slope) of the features increases linearly with lamp current until a tipping point is reached, measured to be 0.8 mA for these laser settings. At higher lamp currents, the absorption attenuates the probe beam reducing the signal size. The lamp current at 0.8 mA is optimized to provide the largest spectroscopy feature for ^{174}Yb , which coincides with the largest peak-to-peak slope for stabilizing the laser frequency. Once obtained for a particular laser system, the lamp current does not need to be changed and the feature sizes become stable.

The second setup provided similar results using a more expensive, off-the-shelf, Moglabs 399 nm laser (Littrow Desmo) and controller (DLC102HC). This setup contained a second optical isolator with an additional 88% transmission and 49 dB isolation. The 398.9 nm light from this laser source was fed into the system of Fig. 4, replacing the ECDL, through a polarization maintaining fiber. The collimated-laser power of the pump beam before the HCL was 2.56(1) mW, with Gaussian $1/e^2$ diameters of 0.26(1) mm in the horizontal direction and 0.24(2) mm in the vertical direction. The diode operating current, as seen on the front display panel, was 54.78 mA, where the lasing threshold was 41.24 mA. The current modulation amplitude for frequency modulation was 1.5 mA. The Moglabs internal dip-switches from 1 to 16 were set to 0101 1000 0000 0000, where 0 and 1 represent the off and on states, respectively. This allowed a feed-forward bias of the ECDL grating piezo-voltage to diode current for a longer mode-hop free tuning range. This ratio can be measured as voltages on Ch A and Ch B of the Moglabs controller, with the channel outputs set to measure the frequency and current, respectively. This ratio of

FIG. 5. Laser induced spectra of neutral Yb, with the frequency axes referenced to the 174 isotope resonance. (a) Absorption signal of the discharge before lock-in detection on the differential photodiode. (b) Laser induced resonance spectra of neutral Yb. (c) Differential photodiode signal after lock-in detection using three different lasers. Assignments of isotope resonances using Table II are shown in gray.

frequency/current was 7.1 to 1. The spectroscopy trace from this laser source is also shown in Fig. 5(c). For this trace, the best results were obtained with a lamp current of 1.4 mA and the dual photodiodes were turned off to reduce the power supply noise. The spectroscopy signal was sent into the current input of the lock-in amplifier, with sensitivity set to 2 mV/V and a low pass filter time constant of 10 ms.

The third, and most expensive, setup used an off-the-shelf M Squared lasers' SolsTiS plus ECD-X system. This laser again provided similar results to the home-built ECDL, where the spectroscopy trace for this laser is also shown in Fig. 5(c). The lock-in settings used for this laser are as follows: sensitivity 5 mV/V, low pass filter time constant 3 ms, and modulation rate 8.52 kHz. A modulation depth of 3 MHz was used. For this laser source, Fig. 5(a) shows the raw absorption signal observed on the positive balanced photodiode. Etalon fringes were evident in this scan. The etalon fringe period and size were consistent with a cavity of 80 cm and 2% reflection. This distance is that between the laser emission asphere and retro-reflecting mirror after the HCL. The irises 20 cm separate from either side of the HCL were close to 1 mm diameter, and a 0.5 ND filter was placed before the retro-reflecting mirror. These optics helped reduce etalon effects in the system. An optical isolator was not implemented for this scan due to spatial constraints. Figure 5(b) shows the POLEAS spectrum corrected for etalon fringes by subtracting a background signal, generated by turning off the HCL power supply.

The natural linewidth for the 398.9 nm $^1S_0 \leftrightarrow ^1P_1$ transition is $\gamma = 2\pi \times 28.9$ MHz.⁵⁴ However, the feature sizes in Fig. 5(b) are close to an order of magnitude larger ($\gamma = 2\pi \times 280$ MHz). The dominant mechanisms for the broadened linewidth are pressure broadening and power broadening. The pressure broadening is estimated to be 36 MHz by a hard sphere model of gas using the covalent radii of neon and ytterbium. The pressure broadened linewidth is then

~65 MHz. The saturation parameter is then approximated, given a probe power of 50(13) μW and a spot size of 0.0421(9) mm^2 as $s_0 = 0.9(2)$. The power broadened linewidth is then estimated as 89(5) MHz, which is an underestimate of the observed linewidth. It is likely that the hard sphere model of pressure broadening is underestimating the collisional cross section of neon and ytterbium since the valence electron of ytterbium is in an excited, large P-orbital. A pressure broadening of 40 MHz/Torr for excited ytterbium colliding with neon would better explain the observed linewidth as in Fig. 5. A comparable pressure broadening of 70 MHz/Torr is seen in He–Ne laser transitions.⁵⁵ The Doppler broadening is approximated to be on the order of 1 MHz given a small angle of acceptance through the irises (5 mrad) around the HCL. This approximated Doppler broadening is less than that previously reported in spectroscopy measurements.^{31,56}

In order to achieve the optimal laser frequency stabilization for a given laser source, we investigated the signal-to-noise ratio (SNR) of POLEAS and PS in terms of pump beam saturation through the lamp. For an operating lamp current of 1.2 mA, the laser intensity from the home-built ECDL was varied with a half-wave plate and PBS, while the beam size and lamp current were kept constant. The signal was defined as the peak-to-peak difference in the voltage of the POLEAS and PS ^{174}Yb spectroscopy features. SNR was defined as the peak-to-peak signal size divided by the root-mean-square noise of the signal when the laser was not in resonance with a spectroscopic feature. In Fig. 6(a), it can be seen that for our given lamp current, the absorption of a beam, through the lamp, saturates at high intensities. In Fig. 6(b), it can be seen that for low intensities, the SNR of POLEAS increases linearly with increased pump beam saturation. This is consistent with creating a larger difference in the absorption coefficient between σ^+ and σ^- transitions.

FIG. 6. Circularly polarized single pass absorbance and signal-to-noise ratio (SNR) of the differential POLEAS and PS signal. Intensity axis set to pump beam intensity before entering the HCL. (a) Pump beam saturation curve. (b) SNR of the prominent ^{174}Yb spectroscopy feature, calculated as the ratio of the signal V_{pp} to noise V_{rms} . Both the signal and noise increased linearly in this intensity regime.

A similar trend is seen for PS. POLEAS has three times the SNR of PS over the range of intensities shown. The dominant noise source after lock-in detection is likely laser intensity noise because the rms noise was measured to increase with laser intensity. The signal size grows linearly with higher input pump beam intensities in this low intensity regime. Using the high-powered SOLSTIS ECD-X laser and a different photoreceiver, the SNR peaks at 645(161) for an intensity of 120(10) mW/mm^2 because of signal saturation. Above this pump beam intensity, the noise on the signal increases, even when using an attenuated return probe beam. The large uncertainty in

FIG. 7. Frequency fluctuation of the stabilized home-built laser, when locked using different spectroscopy techniques, (a) as a function of averaging time τ . Fractional frequency fluctuation [Allan deviation $\sigma(\tau)$] scale bar on the left. Absolute frequency fluctuations on the right. The results are from 1 h (POLEAS), 35 min (PS lock in), and 1 h (PS direct) measurements. The lock-in settings are as follows: sensitivity 500 $\mu\text{V/V}$, integration time 3 ms, and modulation rate 50 kHz. The $\sigma(\tau)$ uncertainty is smaller than the marker size. The covariance plots show the 399 nm laser frequency difference from mean while locked using: (b) POLEAS, (c) PS lock in, and (d) PS direct and their relation to the difference from mean of a locked Vescent 780 nm laser and rubidium spectroscopy module. The fractional frequency difference scale is shown on the bottom and left. The absolute frequency difference scale is shown on the top and right.

measurement is due to polarization drift from coupling high intensity light into the polarization maintaining fiber. This was a worse system configuration compared to the more stable free space source of light from the home-built ECDL.

The lock-in amplified signal of the ytterbium-174 POLEAS feature is used as an error signal for a locking loop. The signal is sent to a proportional-integral-derivative (PID), which sends its output to a piezo connected to the grating of the ECDL. This locking method is compared against the stabilizing method of PS by modifying the optics in the spectroscopy system. To switch our setup in Fig. 4 to PS, the quarter wave plate is moved to the left of the pickoff, and a half wave plate is put in its place, in front of the HCL. Both the direct signal of PS and the lock-in amplified signal of PS were used as error signals in locking loops. Measurements involving the lock-in amplifier were taken with identical settings: 500 $\mu\text{V/V}$ sensitivity, 50 kHz modulation rate, 3 ms integration time, and 25 MHz modulation depth. Drift measurements were made of these laser stabilizing systems using a High Finesse WS8-2 wavemeter. These measurements are compared against measurements of a reference Vescent D2-100-DBR 780 nm laser locked via PS to a D2-110 rubidium spectroscopy module. This reference laser reliably exhibits a sub-100 kHz stability. Measurements of the 399 nm laser take 12 ms of integration. A wavemeter switch then takes 12 ms to multiplex from the 399 nm laser to the 780 nm laser. The 780 nm laser also then takes 12 ms of integration time and 12 ms of switching time. The total measurement period is 48 ms and is repeated in measurement runs of 1 h (POLEAS lock-in amplified), 35 min (PS lock-in amplified), and 1 h (PS direct signal). From the Allan deviation graph shown in Fig. 7, we observe that POLEAS locking has a similar short term frequency instability to PS when taking the lock-in amplified signal. In long-term timescales, the instability diverges with POLEAS being approximately an order of magnitude more stable at 10^3 s of averaging time. Figure 7 shows the covariance between the two locked lasers measured on the wavemeter. Their covariance shows minimal wavemeter drift over the course of measurements. We have previously taken comparable Allan deviation measurements locking to a wavemeter as Ref. 57; however, these do not show long-term instability since they are measured and stabilized off the same instrument.

Even with these drifts, we observe that during the 3600 s measurement time, the maximum Allan deviation was ~ 300 kHz, which is well within the 28.9 MHz linewidth of the atomic transition, and this is in line with our observations that the laser lock is sufficient to allow us to drive the transition and selectively photoionize the different isotopes of ytterbium.

V. CONCLUSIONS

In summary, we have successfully demonstrated the POLEAS locking technique with neutral Yb atoms in a hollow cathode discharge lamp for stabilizing a 398.9 nm laser to the $^1S_0 \leftrightarrow ^1P_1$ transition of several Yb isotopes.

For narrow-linewidth applications such as ultra-cold Bose-Einstein condensates, this technique may require an external modulator to prevent the sidebands from interfering with the laser beam delivered to the experiment. The locking bandwidth of this method is limited by the 1 ms integration time of the lock-in amplifier.

A greater locking bandwidth (into the acoustic regime) could be achieved with a faster lock-in amplifier.

This locking technique has shown to provide the necessary frequency stability to reliably photoionize the selected isotope of ytterbium from a naturally abundant source. Furthermore, the frequency stability measured would be sufficient for laser decelerating Yb atoms in a Zeeman slower for experiments utilizing neutral Yb. By using commercially available equipment and a simple optical setup, our approach significantly simplifies that taken compared to designing and building a Yb vapor cell or transfer cavity. We present this as a simple, robust solution for frequency stabilizing the 398.9 nm laser for atomic physics experiments using Yb atoms and Yb^+ ions.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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