Frequency locking of a 399-nm laser referenced to fluorescence spectrum of an ytterbium atomic beam

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The laser cooling of ytterbium (Yb) atoms needs a 399-nm laser which operates on the strong $^1S_0 - ^1P_1$ transition and can be locked at the desired frequencies for different Yb isotopes. We demonstrate a frequency locking method using the fluorescence spectrum of an Yb atomic beam as a frequency reference. For unresolved fluorescence peaks, we make the spectrum of the even isotopes vanish by using the strong angular-dependence of the fluorescence radiations; the remained closely-spaced peaks are thus clearly resolved and able to serve as accurate frequency references. A computer-controlled servo system is used to lock the laser frequency to a single fluorescence peak of interest, and a frequency stability of 304 kHz is achieved. This frequency-locked laser enables us to realize stable blue magneto-optic-traps (MOT) for all abundant Yb isotopes.

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Ytterbium (Yb) is a metal element with reasonable abundances of both bosonic and fermionic isotopes. It has an alkaline-earth-like electronic structure and long-lifetime triplet states. Besides, the bosonic isotopes have the simplest hyperfine structure due to the zero nuclear spin. These features of Yb have found wide applications in the areas of optical clock[1−3], quantum information[4−6], and parity nonconservation tests[7]. So far, both bosonic and fermionic isotopes have been cooled to quantum degeneracy to investigate the novel quantum phenomena in systems of Bose-Bose[8], Bose-Fermi[9], and Fermi-Fermi mixtures[10].

The strong $^1S_0 - ^1P_1$ transition of Yb atoms, which has a wavelength of 399 nm and a natural linewidth of 28 MHz, is of particular importance in the preparation and probing of cold atomic samples. Laser lights operating on this transition are required not only in the implementation of Zeeman slowing, magneto-optic-traps (MOT), but also in the optical probing of cold atomic clouds, such as the absorption imaging and fluorescence detection. Inevitably, in these applications, the 399-nm laser must be frequency locked to achieve instability much less than the natural linewidth.

Usually, an ytterbium hollow-cathode lamp (HCL) filled with buffer gases (Ne or Ne+Xe mixture) is employed in the frequency locking system. Kim *et al.* demonstrated a modulation-free dichroic-atomic-vapor laser lock (DAVLL), and a frequency stability below 1 MHz was achieved[11]. The DAVLL method features a wide frequency capture range and hence a robust locking. However, a separate atomic transition signal is required to determine the laser detuning from the transition of an isotope. Using Doppler-free saturated absorption signal (DFSAS) of ^{174}Yb, Park *et al.* reached a better frequency stability of 62 kHz[12]. Note that, the attained saturated absorption peaks are still substantially wider than the natural linewidth, wich causes similar difficulty as in DAVLL in the calibration of laser detunings. In addition, the DFSAS signals of the isotopes with significantly lower abundances are rather weak, which seems to be inappropriate for stable frequency locking. Meanwhile, the modulation transfer spectroscopy of Yb atoms in a HCL was demonstrated by Wang *et al.*[13], which shows a similar linewidth as the DFSAS.

Notably, for the 399-nm transition, there exist two groups of closely-spaced lines from different isotopes, both of which includes a line of an even isotope[14]. Since these closely-spaced transition lines have spacings comparable to the natural linewidth, they usually overlap with each other, and hence cannot act as accurate frequency references[15,16].

In this letter, we demonstrate a frequency-locking method based on the fluorescence spectrum of an Yb atomic beam. The well collimated atomic beam ensures a narrow linewidth of the fluorescence peaks. In addition, by changing the polarization direction of the exciting light, the peaks corresponding to the even isotopes may vanish completely. The remained closely-spaced peaks are thus well resolved, and can be treated as accurate frequency references for laser locking. Our 399-nm laser can be locked to each resolved peak, and a frequency stability well bellow 1 MHz is attained. Stable Magneto-optical-traps (MOT) of each abundant isotopes have been realized using this laser.

Our experimental setup is sketched in Fig. 1. An Yb oven is mounted on one end of a vacuum system which has multiple optical windows. The whole vacuum chamber is pumped by a 40-L/s ion-pump to a pressure level of 10^{-6} Pa. The oven is heated to a temperature of 437 °C. Thermal atoms exit the oven through a long collimating nozzle, and then pass a small aperture (not shown in the figure), forming an atomic beam with a small divergence

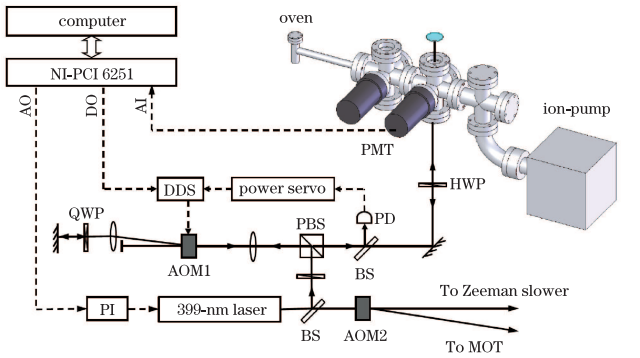

Fig. 1. Schematic of the experimental setup. Solid and dashed lines show the light path and electronic connections, respectively. AOM: acousto-optic modulator; BS: beam splitter; PBS: polarizing beam splitter; PD: photo-diode; DDS: digital direct synthesizer; PMT: photomultiplier tube; QWP: quarter-wave plate; HWP: half-wave plate; PI: proportional-integrator; AI/AO: analog-digital converter input/output port; DO: digital output port.

of 3 mrad. A retro-reflected laser beam perpendicular to the laser beam is used to excite the Yb atoms. The fluorescence of the excited atoms is collected by an optical lens and detected by a photomultiplier tube (PMT) placed near a side window. Since the solid angle of light collection is small (∼0.02), the observation direction of the fluorescence can be approximated by the axis of the collection lens which is orthogonal to both the laser beam and the atomic beam. The well collimated atomic beam greatly reduces the Doppler broadening, allowing us to obtain narrow fluorescence peaks. The measured full-width at half-maximum (FWHM) of a typical peak is 33 MHz, only 20% larger than the natural linewidth.

The 399-nm laser light is derived from a commercial laser (DL-TA-SHG pro, Toptica Inc.) of an output power up to 130 mW. While most of the power is delivered to the MOT and Zeeman slower, only a small portion of the laser light is used for fluorescence spectra. This part of light is firstly sent to a double-passed AOM, and then directed to illuminate the atomic beam. This AOM is mainly used to scan the laser frequency within a range of 40 MHz which is wide enough to cover a fluorescence peak. To ensure the frequency accuracy, the driver of the AOM is based on a home-made direct digital synthesizer (DDS) with a frequency resolution better than 10 kHz and a very low frequency drift rate (<1 kHz/h). On the other hand, the light power from the double-passed AOM is monitored by a photodiode and servo-controlled by the same AOM. A power stability better than 1% is attained during the scanning time. The laser light to excite the atoms is linearly polarized, and the polarization vector can be rotated by a half-wave plate.

Before locking the laser frequency to a transition line, we must manually tune the laser so that the corresponding fluorescence peak appears in the scanning range of the AOM. If we close the servo loop, the laser frequency is then locked to the top of the peak as the servo cycle is repeated continuously. Each servo cycle lasts for 25 ms. During the first 10 ms, the AOM scans the laser frequency, and the fluorescence signal is recorded using a multifunction data acquisition card installed in a computer. In the last 15 ms, the computer calculates the frequency position corresponding to the top of the fluorescence peak, and also outputs an error signal. The deviation of the peak position from the middle point of the scanning range is a measure of the frequency excursion of the laser. The error signal, which is proportional to the frequency excursion, is filtered with a proportional-integrator, and then applied to the frequency tuning port of the laser. Given the negative feedback, the fluorescence peak is finally pulled back to the middle point of the scanning range.

Figure 2 displays the measured frequency excursion of the 399-nm laser when locked to the peak of ^{174}Yb. Apparently, the laser frequency fluctuates around the locking point within a range of 1 MHz. The distribution of the frequency excursion is plotted in the inset of Fig. 2. A Gaussian fitting to the histograms shows a standard deviation of 304 kHz, which represents the stability levels of the laser frequency.

Special attention must be paid to overlapped peaks. As shown in Fig. 3(a), there exist two group of closely spaced transitions. The left group consists of three transitions, ^{173}Yb($F = 5/2 \rightarrow 3/2$), ^{172}Yb and ^{173}Yb($F = 5/2 \rightarrow 7/2$), while the right group has only two transitions, ^{171}Yb($F = 1/2 \rightarrow 1/2$) and ^{170}Yb. The peaks of the closely spaced transitions overlap with each other, forming a broad structure. Apparently, overlapped peaks can not serve as accurate frequency references since it not easy to identify the frequency positions of the included transitions. In this case, it is hard to know the actual laser detuning from a transition even if the laser is already locked to a certain point on the broad structure. To solve this problem, we need to intentionally prevent the appearance of some transitions in the fluorescence spectra by using the angular dependence of the fluorescence radiation.

Note that, the dipole radiation of an atom can be anisotropic. Zinkstok *et al.* had calculated the angular distribution of fluorescence at the $^1S_0 - ^1P_1$ transition for all Yb isotopes assuming excitation with linearly polarized light[17]. The even isotopes, due to their zero nuclear spin, show the same anisotropic distribution in the form of $\sin^2(\theta)$, where θ refers to the angle between the observation direction and linear polarization vector of the exciting laser. By contrast, the odd isotopes, which

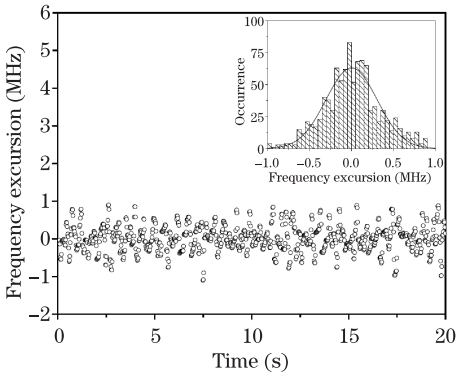

Fig. 2. Frequency excursion of the 399-nm laser at the locking state as a function of time. The vertical scale corresponds to the measured frequency deviation from the center of the scanning range. Histograms of the inset count the data points within each frequency interval of 0.05 MHz, while the solid curve is a gaussian fitting which shows a standard deviation of 304 kHz.

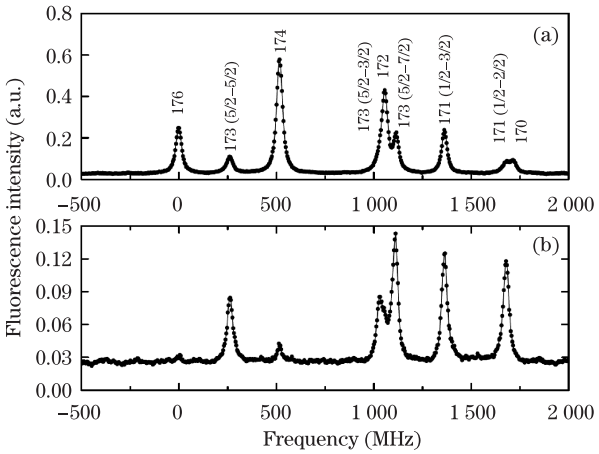

Fig. 3. Fluorescence spectrum of an Yb atomic beam at the 399-nm ${}^1S_0 - {}^1P_1$ transition. The x axis represents the frequency shift from the transition of ^{176}Yb. The polarization direction of exciting light is (a) perpendicular and (b) parallel to the observation direction, respectively.

have a non-zero nuclear spin, have a much more isotropic distribution.

For even isotopes, the strong angular dependence of the fluorescence radiation allows us to let the fluorescence peaks vanish by choosing a special observation angle, $\theta = 0$. To change θ, we rotate the polarization direction of the excitation laser while keeping the photo-detector at a fixed position. This step is much more convenient than moving the photo-detector.

Figure 3 displays the spectra at two extreme cases. When θ is set to $\pi/2$ (Fig. 3(a)), the fluorescence peak of each even isotope reaches a maximum intensity. Two groups of overlapped peaks are observed as mentioned previously. In contrast, when $\theta = 0$ (see Fig. 3(b)), the peaks of the even isotopes become much weaker and even discernable compared with the peaks of other isotopes. These peaks did not disappear completely as expected due to the fact that the fluorescence was actually detected within a small range around $\theta = 0$. Nevertheless, they are too weak to modify the shapes of adjacent peaks overlapping with them, and are hence negligible.

In absence of the even isotope peaks, all of the remained peaks can be clearly identified. Looking at the two peaks of ${}^{173}\mathrm{Yb}(F = 5/2 \rightarrow 3/2)$ and ${}^{173}\mathrm{Yb}(F = 5/2 \rightarrow 7/2)$ which are spaced by 72 MHz, we can see that they are well resolved now, although still partially overlapped. Additionally, the transition of ${}^{171}\mathrm{Yb}(F = 1/2 \rightarrow 1/2)$ shows as a fully separated peak, having no overlap with other peaks any more. Apparently, the two stronger peaks, ${}^{173}\mathrm{Yb}(F = 5/2 \rightarrow 7/2)$ and ${}^{171}\mathrm{Yb}(F = 1/2 \rightarrow 1/2)$, are now able to serve as frequency references. In fact, we had locked the laser to these two peaks, and attained the same frequency stability as in Fig. 2.

As to the even isotope transitions belonging to the closely spaced group, i.e. ^{170}Yb and ^{172}Yb, we cannot extract them from the adjacent peaks regardless of the observation angle chosen. However, the two transitions can be accessed by shifting the frequency of the main laser beam while the laser is locked to adjacent transitions of the odd isotopes. Given that the distance between closely spaced transitions is on the order of several tens of magahertz, the desired frequency shift can be simply realized through a regular AOM (AOM2 in Fig. 1). The detunning of the laser beam used for MOT can inevitably be set by the AOM2.

Table 1. Atomic Numbers in The Blue MOT of Ytterbium

^{170}Yb	^{171}Yb	^{172}Yb	^{173}Yb	^{174}Yb	^{176}Yb
5.1×10^6	4.6×10^6	1.9×10^7	2.7×10^6	2.2×10^7	1.6×10^7

Using the frequency-locked laser, we have achieved a stable blue MOT which can operate in a steady state for several hours. The optical system of the blue MOT was described elsewhere[18]. The typical numbers of trapped atoms in the MOT are listed in Table 1. Almost all isotopes are trapped by the MOT except the least abundant ^{168}Yb.

The frequency locking method described above can be easily extended to a 556-nm laser used for the green MOT operating on the ${}^1S_0 - {}^3P_1$ inter-combination transition. We lock a 556-nm laser using the same atomic beam, and obtained a frequency stability of ~ 100 kHz[19]. Although the natural linewidth of the inter-combination line is much smaller than that of the 399-nm transition, its fluorescenc-e peaks are not so narrow due to residual Doppler broadening of the atomic beam. This phenomenon imposes a limitation on the achievable frequency stability. Nevertheless, we found in our experiment that the frequency locked 556-nm laser is good enough for a green MOT.

In conclusion, we lock a 399-nm laser to the ${}^1S_0 - {}^1P_1$ transition of Yb using the fluorescence spectrum of an atomic beam as a frequency reference. A frequency stability of 304 kHz is achieved when the laser is locked to a single fluorescence peak. For closely spaced peaks overlapped with each other, we prevent the even isotopes from appearing in the fluorescence spectrum by using their strong angular dependence in the fluorescence radiation. The remained closely-spaced peaks are thus well resolved to serve as accurate frequency references. The frequency locked laser is employed to realize a stable blue MOT for all Yb isotopes except the least abundant one. This frequency locking method is also successfully applied to a 556-nm laser for green MOT.

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