

## Efficient magneto-optical trapping of Yb atoms with a violet laser diode

Chang Yong Park and Tai Hyun Yoon\*

Center for Optical Frequency Control, Korea Research Institute of Standards and Science, 1 Doryong, Yuseong, Daejeon 305-340, Korea

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We report an efficient trapping of rare-earth-metal Yb atoms with a high-power violet laser diode (LD). An injection-locked violet LD with a 25-mW frequency-stabilized output was used for the magneto-optical trapping (MOT) of fermionic as well as bosonic Yb isotopes. A typical number of  $4 \times 10^6$  atoms for  $^{174}\text{Yb}$  with a trap density of  $\sim 1 \times 10^8 \text{ cm}^{-3}$  was obtained. A 10-mW violet external-cavity LD was used for the one-dimensional slowing of an effusive Yb atomic beam without a Zeeman slower resulting in a 35-fold increase in the number of trapped atoms. The overall characteristics of our compact violet MOT, e.g., the loss time of 1 s, the loading time of 400 ms, and the cloud temperature of 0.7 mK, are comparable to those in previously reported violet Yb MOTs, yet with a greatly reduced cost and complexity of the experiment.

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Atomic rare-earth-metal ytterbium (Yb) has been proposed as one of the ideal neutral atomic systems for a future optical frequency standard [1] due to its unique energy-level structure that is very similar to the alkali-earth-metal counterparts, Ca [2,3], Sr [4], and Mg [5], which have a strong closed dipole-allowed transition for laser manipulation along with a narrow intercombination transition for optical clock excitation. Recently, Katori proposed a unique approach to develop an optical frequency standard based on the  $^1S_0$ - $^3P_0$  doubly forbidden intercombination transition in the  $^{87}\text{Sr}$  fermionic isotope [6]. In the proposal, cold fermions are trapped within the Lamb-Dicke region in a Stark shift-free optical trap [7], which is believed to be an ideal cold atomic system for a long interrogation time without residual Doppler shift, thus providing a low systematic uncertainty comparable to the single-ion-based optical frequency standard [8]. To realize this proposal, a recoil-limited laser cooling of  $^{87}\text{Sr}$  atoms near the Fermi temperature in an optical lattice and a recoil-free spectroscopy of neutral Sr atoms in the Lamb-Dicke regime have been demonstrated [9,10]. Quite recently, Courtillot *et al.* successfully detected the weak  $^1S_0$ - $^3P_0$  transition in a conventional  $^{87}\text{Sr}$  magneto-optical trapping (MOT) and measured the absolute frequency of the transition with a femtosecond comb [11].

In the Yb atomic system, there are two stable fermionic isotopes, i.e.,  $^{171}\text{Yb}$  ( $I=1/2$ ) and  $^{173}\text{Yb}$  ( $I=5/2$ ), where  $I$  is the nuclear spin. We believe that for the fermionic Yb isotopes, Katori's proposal could equally be applicable for both fermions and even  $^{171}\text{Yb}$  may compete with  $^{87}\text{Sr}$  for the future optical frequency standard due to its simple magnetic sublevel structure. For this application, efficient one-dimensional (1D) slowing and trapping of Yb atoms using a resonant  $^1S_0$ - $^1P_1$  transition at 398.9 nm can be the starting point of the whole road to an Yb optical clock. Recently, high-density trapping and the first Bose-Einstein condensation of Yb atoms by an optical dipole trap loaded from an intercombination MOT (555.8 nm) [12,13] and sub-Doppler cooling effects of the fermionic Yb atoms [14] have been reported. We can expect other interesting applications using

the trapped Yb atoms if one can build a compact violet laser system at 399 nm which can be used for the efficient 1D slowing and first-stage violet MOT [15–17] as demonstrated in this study. Usually, a frequency-doubled Ti:sapphire laser is used for that purpose, but the system is complex and expensive; therefore a study of a compact yet inexpensive violet laser diode (LD) system for the efficient trapping of Yb atoms would be of importance for future applications.

With the recent developments of violet LD technologies, a high-power (30-mW) violet LD is now commercially available. Based on this high-power violet LD, we have reported previously a frequency-stabilized, high-power, violet LD system for the manipulation of Yb atoms [18,19]. In this paper, we describe the demonstration of an efficient Yb trapping experiment in a conventional MOT by using the violet LD system. The performance characteristics of our compact violet MOT, for example, the trapped atom number of different isotopes, are found to be similar to those of the previously reported Yb MOT by using a frequency-doubled Ti:sapphire laser [20], yet with a greatly reduced cost and complexity of the experiment. In addition, for a future optical clock studies, we have successfully trapped  $1.4 \times 10^6$  fermionic  $^{171}\text{Yb}$  atoms with a temperature of 0.7 mK, which is very close to the Doppler limit of  $670 \mu\text{K}$ .

Figure 1 shows the layout of our experimental setup for the efficient trapping of Yb from an atomic beam effusing from an oven, but without a Zeeman slower. The experiments were done inside an ultrahigh vacuum chamber consisting of a commercial stainless octagon. The octagon was pumped by two 45 l/s ion pumps and maintained at a pressure of  $4 \times 10^{-10}$  torr without Yb atoms and  $6 \times 10^{-9}$  torr with the Yb atomic beam at the oven temperature of  $390^\circ\text{C}$ . The trapping laser beam from the slave laser (described below) was divided into two beams by a beam splitter for the horizontal axis ( $X$  and  $Y$  axes) and the vertical axes ( $Z$  axis). The horizontal beam was retroreflected in the  $X$ - $Y$  plane, while the vertical beam was retro-reflected in the  $Z$  axis, to form a three-dimensional  $\sigma^+$ - $\sigma^-$  trapping geometry. Since the intensities  $I$  of the two trapping beams were only  $5.0 \text{ mW/cm}^2$  just before the windows of the octagon, the saturation parameter  $s$  was very small, i.e.,  $s = I/I_s = 0.09$ , where  $I_s = 2\pi\hbar\omega\Gamma/6\lambda^2 = 58 \text{ mW/cm}^2$  is the saturation in-

\*Electronic address: thyoona@kriss.re.kr

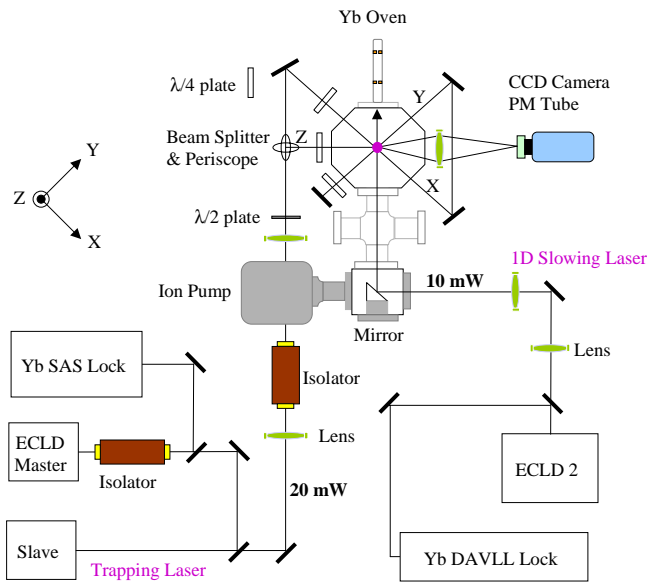


FIG. 1. Optical layout of the efficient trapping of a 1D-slowed Yb atomic beam with a violet LD system, without a Zeeman slower.

tensity,  $\Gamma = 2\pi \times 28$  MHz (excited-state decay rate),  $\omega = 2\pi c/\lambda$ ,  $c$  is the velocity of light, and  $\lambda$  is the wavelength of the trapping laser. Therefore, we attached the oven close to the octagon (8 cm apart) to increase the atomic flux and used a 1D-slowing laser to increase the number of low velocity atoms below the capture velocity  $v_c \approx 15$  m/s of the violet MOT [3]. At 390 °C the fraction of Yb atoms under  $v_c$  is estimated to be  $3.5 \times 10^{-6}$ . And by assuming the flux of Yb atoms from the oven is  $10^{11} - 10^{12}/s$  for our trap geometry (nozzle diameter of 1.5 mm and 20 cm distance between the oven exit and the trap center) [16], we could roughly estimate the flux of Yb atoms slower than  $v_c$  by using the Maxwell-Boltzmann distribution, namely, the loading rate of  $10^4 - 10^5/s$  without any 1D-slowing process. Therefore, the use of a 1D-slowing laser is essential for the efficient trapping of Yb atoms. In addition, to maintain a steep magnetic-field gradient and an ultrahigh vacuum in the octagon, we designed a compact anti-Helmholtz coil installed outside the octagon with coils separated by only 4 cm. In the experiment, we found an optimal value of  $\partial B/\partial z = 45$  G/cm at the coil current of 3.5 A and the trapping laser detuning of  $-0.5\Gamma$ .

To build a trapping laser at 398.9 nm, we developed a high-power violet LD system employing the injection-locking technique. Details of the master+slave violet laser system were previously reported in Ref. [19], and here we only briefly describe the system. The violet LDs used for the master external-cavity LD (ECLD) and the slave laser are high-power violet LDs with a 30 mW output power. The master ECLD has a Littrow geometry in external feedback and has an output power of more than 15 mW [18]. The frequency of the master ECLD could be locked to any of the dispersion slopes of the Doppler-free absorption signals corresponding to the six stable Yb isotopes, i.e., isotopes 170, 171–174, and 176, obtained in the Yb saturation spectrometer (Yb SAS lock). The Yb SAS consisted of a Yb hollow-

cathode lamp (HCL) with Ne buffer gas. However, we could not resolve the closely positioned absorption lines corresponding to the two hyperfine transitions of the  $^{173}\text{Yb}$  [ $^1S_0(F=3/2)$  to  $^1P_1(F'=3/2)$  and  $^1P_1(F'=7/2)$ ] and  $^{172}\text{Yb}$  isotopes [19]. Since the Doppler-free width of 60 MHz is more than two times wider than the natural linewidth of the  $^1P_1$  excited state, we were easily able to tune the frequency of the master laser to the optimal red detuning of  $-0.5\Gamma$  with an electronic servo system [19]. We have estimated the frequency stability of the master ECLD from the measurement of Allan variance of its error signal and obtained a frequency stability of 62 kHz at a 1 s average time. Consequently, with a 0.6 mW injection power, the stabilized output of the master laser increased coherently up to 25 mW with the slave laser. The beat-note linewidth at 160 MHz between the master and slave lasers was measured to be below 1 Hz, indicating a good injection-locking quality with a stability of  $2.5 \times 10^{-7}$  at a 1 s average time [19].

A violet ECLD for the 1D slowing (ECLD2) was also constructed with the same high-power violet laser diode. The frequency of the 1D-slowing laser was stabilized to the broad Doppler-limited absorption signal having a 2-GHz-wide linewidth obtained with the modulation-free DAVLL (dichroic-atomic-vapor laser lock) technique (Yb DAVLL lock) [18]. Due to its broad spectrum associated with the six Yb isotopes, we were easily able to find the optimal detuning of the 1D-slowing laser for a specific isotope by changing electronically the reference voltage of the locking signal. A 10-mW output of the ECLD2 was focused through a side window of the vacuum chamber as shown in Fig. 1 to the exit of the oven collimator (not shown) [3] to maximally overlap the 1D-slowing laser with the atomic beam at the center of the violet MOT, taking into account the atomic beam divergence. With this focused 1D-slowing laser, we achieved an increased acceleration and power broadening simultaneously along the direction toward the exit of the oven, which resulted in an increase of the total number of 1D-slowed atoms in the trap site by as large as 35 times than that without the 1D-slowing laser.

Individual Yb isotopes could be sequentially loaded into the violet MOT by changing the locking point of the trapping laser to correspond to a detuning of  $-0.5\Gamma$  and slowly scanning the 1D-slowing laser frequency across the  $^1S_0 - ^1P_1$  resonance. As a result, we were able to trap almost all of the stable Yb isotopes. Figure 2 shows the fluorescence intensities for different Yb isotopes as a function of the detuning of the 1D-slowing laser from the frequency of the trapping laser. We found that the optimal detunings of the 1D-slowing laser were about  $-90$  MHz ( $\sim -3.2\Gamma$ ) for the bosonic isotopes and  $-80$  MHz ( $\sim -2.9\Gamma$ ) for the fermionic  $^{171}\text{Yb}$  isotope. The difference of the optimal detuning of the 1D-slowing laser in the fermionic isotope could be understood as resulting from optical pumping between the hyperfine sub-levels present because of the nonzero nuclear spin. Note that the detuning of the 1D-slowing laser in our experiment is relatively close to the line center compared to the experiments using a Zeeman slower [15,16].

We measured the average cloud diameter of 2.5 mm full width at half maximum by imaging the violet MOT onto the

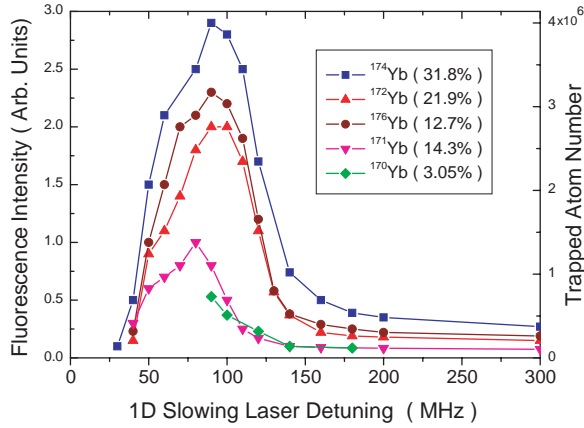


FIG. 2. Fluorescence intensity and trapped atom number as a function of detuning of the 1D-slowing laser for different Yb isotopes. The trapped atom numbers are calibrated from the spectral sensitivity data of the PM tube and the imaging geometry in Fig. 1. Inset shows the Yb isotope atomic numbers and their natural abundances in parentheses.

image plane of the collection lens (see Fig. 1) to measure the density of trapped atoms. Fluorescence intensity from the MOT was easily measured with either a power meter or a photomultiplier (PM) tube located at the image plane of the trapped Yb cloud, enabling us to calibrate and calculate the trapped atom numbers taking into account the solid angle of the imaging lens and the scattering rate of the  $^1S_0$ - $^1P_1$  transition. The maximum trapped atom number and density of the most abundant  $^{174}\text{Yb}$  isotope were about  $4 \times 10^6$  and  $1 \times 10^8 \text{ cm}^{-3}$ , respectively. The vertical axis in the right-hand side of Fig. 2 indicates the calibrated trapped atom number. Table I summarizes the maximum trapped atom numbers and natural abundances for different Yb isotopes. Note that the trapped atom numbers listed in Table I are just half of those in Refs. [20,17], where no 1D-slowing laser was used but a high-power (80–90 mW,  $s=0.5$ – $0.6$  per axis) frequency-doubled Ti:sapphire laser for trapping was employed, demonstrating the high efficiency of the violet LD trapping of Yb atoms with a 1D-slowing laser. Furthermore, this result can also be explained with the earlier observation of the power dependent loss mechanism in Ref. [16]. The higher intensity of the trapping laser increases the excited-state population  $\rho_{22}$  and subsequently increases the population loss in the Yb MOT through a weak branching via the  $^3D_1$  and  $^3D_2$  states

TABLE I. Natural abundance (NA), maximum trapped atom number (TN), trapped atomic temperature (CT), loading time (LT), decay time (DT), and recapture ratio (RR) for different Yb isotopes in the violet MOT.

Isotope	NA (%)	TN	CT (mK)	LT (s)	DT (s)	RR
170	3.1	$7.0 \times 10^5$	1.0	0.8	0.5	0.4
171	14.3	$1.4 \times 10^6$	0.7	0.7	0.6	0.6
172	21.9	$3.2 \times 10^6$	0.7	0.5	0.9	0.6
174	31.8	$4.9 \times 10^6$	0.7	0.4	1.0	0.6
176	12.7	$2.8 \times 10^6$	0.7	1.0	0.9	0.6

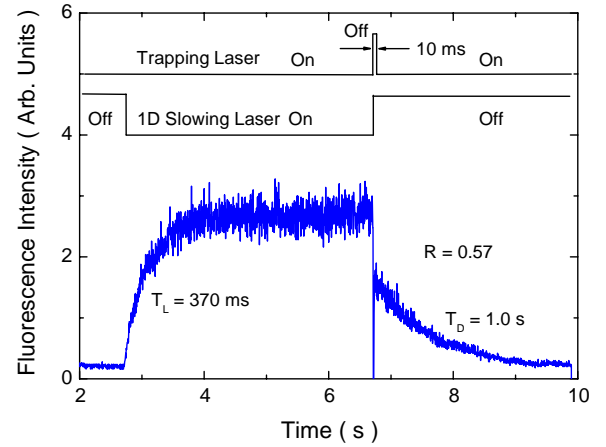


FIG. 3. Temperature measurement of the  $^{174}\text{Yb}$  isotope in the violet MOT by using a release-and-recapture method along with the loading time  $T_L$  and decay time  $T_D$  measurements.

to the  $^3P_2$  and  $^3P_0$  metastable states resulting in the saturation of the total trapped atom numbers at the low-level intensity ( $s < 1$ ) of the trapping laser.

The fluorescence intensity ratios between the even isotopes (172, 174, and 176) were very similar to the natural abundance ratios between them [15,20]. However, for the fermionic  $^{171}\text{Yb}$  isotope the trapping efficiency was 50% smaller than those of the even isotopes [15,20]. In Fig. 2, we omitted the fluorescence intensity corresponding to the fermionic  $^{173}\text{Yb}$  isotope, since we could not observe a confined atomic cloud, rather we were just able to detect the fluorescence from the optical molasses state. This fact can be understood because the  $^1P_1$  ( $F'=7/2$ ) hyperfine state of  $^{173}\text{Yb}$  lies too close to the  $^1P_1$  ( $F'=3/2$ ) state (84 MHz apart), and thus optical pumping to the magnetic sublevels in the  $^1S_0$  ( $F=5/2$ ) ground state disturbs the cyclic cooling process [15]. In addition, in this level configuration the trapping beam is always blue detuned from for the  $^1P_1$  ( $F'=3/2$ ) state, producing an opposite force relative to the trapping force by the  $^1P_1$  ( $F'=7/2$ ) cycling transition due to the opposite sign of the Landé  $g$  factors. This problem could be solved by using the second-stage intercombination trapping transition at 555 nm demonstrated in Ref. [15], where the excited hyperfine intervals of the three  $^3P_1$  hyperfine states of the  $^{173}\text{Yb}$  isotope are well separated ( $> 1.5$  GHz). The hyperfine splitting of the excited state of  $^{171}\text{Yb}$ , however, is 319 MHz wide, therefore there is no optical pumping effect in the  $^{171}\text{Yb}$  isotope. As shown in Fig. 2, we have trapped  $1.4 \times 10^6$   $^{171}\text{Yb}$  atoms with high efficiency (35% of the most abundant  $^{174}\text{Yb}$  isotopes) which is slightly lower than the result in Ref. [20], close to the natural abundance ratio of 45% between them (see Table I). Consequently, we expect that in future studies of optical clocks based on the fermionic  $^{171}\text{Yb}$  isotope, the violet LDs will be very useful for the preparation of the cold trapped  $^{171}\text{Yb}$  atomic samples.

To characterize the violet MOT further, we have measured the cloud temperature, the loading time  $T_L$ , and the decay time  $T_D$  of the MOT by using the well-known release-and-recapture method. The bottom trace in Fig. 3 shows the typical experimental data for the loading time and decay time



measurements of the  $^{174}\text{Yb}$  isotope. Upper traces in Fig. 3 show the chopping time sequences of the trapping and 1D-slowing lasers for two mechanical shutters installed in front of the slave laser and ECLD2 in Fig. 1. After loading the MOT with the trapping laser only, we suddenly turned on the 1D-slowing laser at  $T=2.7$  s, as shown in Fig. 3, to see the increase of fluorescence intensity with the help of the 1D-slowing laser. From the exponential fit to the data, we could obtain the loading time of  $T_L=370$  ms. As one can see from Fig. 3, the use of the 1D slowing laser increased the trapped atom number by about 35 times more than that obtained with the trapping laser only. After the steady state was reached, we abruptly turned off both lasers at  $T=6.7$  s to let the atomic cloud freely expand, and 10 ms later we turned on the trapping laser again, thereby re-capturing the atoms by the trapping laser only. Then, the fluorescence intensity decays with the same decay rate of the MOT until the steady state is reached. From the exponential fit to this decay curve, we obtained the decay time of  $T_D=1.0$  s. We repeated the measurement for the different Yb isotopes and listed the measurement results in Table I. The difference between the loading rate and the decay rate in Fig. 3 and Table I is caused by the fact that the detuning of our 1D-slowing laser is only  $3\Gamma$  from the line center and there is a 1D radiation pressure which increases the loss rate of the violet MOT when the 1D-slowing laser is turned on.

Since we know the size of the trapping beam (1 cm), we can estimate the cloud temperature by measuring the fluorescence intensity ratio  $R$  before and after the 10-ms interval at  $T=6.7$  s in Fig. 3. If we assume a three-dimensional isotropic Boltzmann velocity distribution at the given temperature  $T$ , and calculate the time evolution of the distribution after 10 ms taking into account the increased cloud size, then it is straightforward to obtain the ratio between the number of atoms within the size of the trapping laser beam to the total number of initially trapped atoms. This ratio should be di-

rectly proportional to the fluorescence intensity ratio depending on the initial cloud temperature as measured in Fig. 3, i.e.,  $R=0.57$  for  $^{174}\text{Yb}$ . By adjusting the initial temperature of the trapped atoms in a fitting program until the calculated ratio of the atomic numbers agrees with the measured ratio  $R$  of the fluorescence intensities, we can determine the temperature of the trapped atoms. Table I also shows the measured fluorescence intensity ratio (recapture ratio)  $R$  and the cloud temperature of the different Yb isotopes. We found that the cloud temperatures for most Yb isotopes were slightly above the Doppler limit of  $670\ \mu\text{K}$  as can be seen in Table I. The relatively low temperature of the trapped Yb atoms observed resulted from the low saturation parameter ( $s=0.09$ ) of the violet LD trapping laser. However, the focused 1D slowing laser increased the total number of trapped atoms, comparable to the results in Refs. [15,20].

In summary, we have efficiently cooled and trapped the rare-earth-metal Yb atoms in a compact violet magneto-optical trap employing a high-power frequency-stabilized violet LD system without a Zeeman slower. The overall characteristics of our compact violet Yb MOT are found to be similar to those of the previously reported Yb MOTs using a frequency-doubled Ti:sapphire laser and a Zeeman slower, yet with greatly reduced cost and complexity. Importantly, for future optical clock studies, we have successfully trapped  $1.4\times 10^6$  fermionic  $^{171}\text{Yb}$  atoms with a temperature of  $0.7$  mK, which is very close to the Doppler limit of  $670\ \mu\text{K}$ . We are now trying to employ a far-off resonant dipole trap, following Katori's proposal [6], to realize a Lamb-Dicke confinement of neutral  $^{171}\text{Yb}$  fermionic atoms for a new Yb optical clock.

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