A robust method for frequency stabilization of 556-nm laser operating at the intercombination transition of ytterbium

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A frequency-stabilized 556-nm laser is an essential tool for experimental studies associated with $^1S_0$-$^3P_1$ intercombination transition of ytterbium (Yb) atoms. A 556-nm laser light using a single-pass second harmonic generation (SHG) is obtained in a periodically poled MgO:$LiNbO_3$ (PPLN) crystal pumped by a fiber laser at 1111.6 nm. A robust frequency stabilization method which facilitates the control of laser frequency with an accuracy better than the natural linewidth (187 kHz) of the intercombination line is developed. The short-term frequency jitter is reduced to less than 100 kHz by locking the laser to a home-made reference cavity. A slow frequency drift is sensed by the 556-nm fluorescence signal of an Yb atomic beam excited by one probe beam and is reduced to less than 50-kHz by a computer-controlled servo system. The laser can be stably locked for more than 5 h. This frequency stabilization method can be extended to other alkaline-earth-like atoms with similar weak intercombination lines.

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The cooling and trapping of ytterbium (Yb) atoms have attracted great attention for their application in time and frequency standards[1,2], photoassociation (PA) and cold collision[3−5], mixture of bosons and fermions[6], as well as charge-parity (CP) violation tests[7]. Recently, an artificial gauge field based on Yb atoms has been proposed[8]. All of these previous studies involved $^1S_0$-$^3P_1$ intercombination transition. The natural linewidth of this line is only 187 kHz, which corresponds to a Doppler limited temperature of 4.5 μK. Therefore, magneto-optical-trapping (MOT) based on this transition is a critical step in obtaining cold atomic samples for subsequent studies[9]. The 556-nm laser for this transition must have a narrow linewidth and small frequency excursion. The study of the PA spectrum also requires a well-stabilized and controlled laser frequency. In an earlier experiment, a continuous-wave (CW) ring dye laser is cascade locked to a Rb saturated absorption line through a transmission cavity[10]. However, cascade locking is hindered by complicated optical and electronic systems. Recently, a 556-nm laser source was obtained by frequency doubling using a periodically poled MgO:$LiNbO_3$ (PPLN) waveguide, which was locked to an ultra-stable optical cavity[11]. Considering that the construction of an ultra-stable optical cavity is complicated and expensive, a simpler and more robust alternative approach is required for frequency stabilization.

In this letter, we report a robust method on the frequency stabilization of a 556-nm laser light produced by a single-pass second harmonic generation (SHG) in a PPLN crystal pumped by a fiber laser at 1111.6 nm. We first lock the laser to a home-made reference cavity to reduce the frequency jitter and then suppress the long-term frequency drift by locking the cavity to a fluorescence peak of an atomic beam excited by one probe beam. The laser frequency reaches a stability of 100 kHz, which is well below the natural linewidth (187 kHz) of the intercombination line. The locking is very robust and can last for more than 5 h. Particularly, the long-term stability is better than 50 kHz. This laser was used to create the green MOT of Yb in our previous work[12]. Our method provides a good substitute for ultra-stable cavity locking and cascade locking, and it is also widely used in the study of other alkaline-earth-like atoms with weak intercombination lines.

The 556-nm wavelength is not accessible by laser diodes but is available for CW ring dye lasers. Frequency doubling of a 1111.6 nm fiber laser light is a more convenient alternative. Recently, PPLN waveguides have been widely used in SHG because of their high conversion efficiency[11,13,14]. A precise optical alignment is required to couple the fundamental light into a waveguide. In our 556-nm laser system, we use a 3-cm-long bulk PPLN crystal instead. Compared with a waveguide structure, the bulk crystal has a much larger optical aperture (3.2×0.5 (mm)), and it allows a high pump power despite the lower frequency-doubling efficiency. Optical alignment is easy to reach and maintain. The fundamental light of the 1111.6-nm wavelength is derived from a CW single-mode Yb-doped fiber laser with an output up to 2 W. The laser beam first passes through an optical isolator and then is coupled into the crystal through two mode-matching lenses, yielding a focused beam with a waist radius of 34 μm at the center of the crystal. The focusing parameter, defined as the ratio of the crystal length to the Rayleigh length, is about 2.07. A half-wave plate is placed before the crystal to align the polarization of the fundamental laser to the vertical direction. The green SHG light is separated from the intense fundamental light by two dichroic mirrors behind the crystal. This crystal is placed

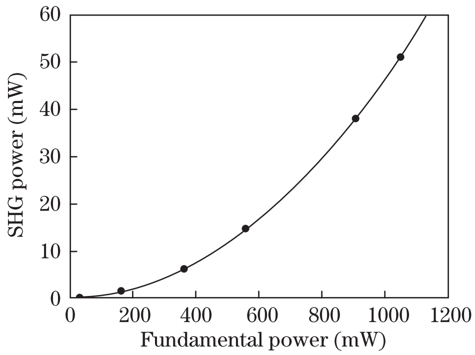

Fig. 1. SHG output as a function of fundamental power. Dots show the experimental data measured at a crystal temperature of 149.6 °C; the fitting curve is $P_{\rm sh} = \gamma_{\rm sh} P_{\rm fund}^2$, where $P_{\rm sh}$ is the SHG power, and $P_{\rm fund}$ is the fundamental power. The SHG efficiency $\gamma_{\rm sh}$ is fitted to be 4.5% W^{-1}.

inside an oven which is temperature controlled to a stability of 0.1 °C, and a teflon cover is put on the top of the crystal to ensure a uniform temperature.

The optimal phase-matching temperature was measured to be 149.6 °C at which the SHG efficiency was maximized. The output of a 556-nm green light laser was measured for a varied fundamental power, as shown in Fig. 1. For a 1-W fundamental input, a 45-mW SHG power was obtained, which corresponded to a conversion efficiency of 4.5% W^{-1}. The saturation intensity of the intercombination line is only 0.14 W/cm^2, so a light power in the order of several tens of milliwatts is high enough for an Yb MOT. We found that the SHG output power is rather sensitive to crystal temperature, and a 5% slow fluctuation is observed due to temperature instability.

Yb metal has a very low vapor pressure at room temperature. In addition, the intercombination line is a weak transition. Therefore, the conventional frequency-locking technique based on a saturated absorption spectrum is not applicable to the 556-nm laser. Instead, locking to a reference optical cavity seems to be a practical choice. We built a simple Fabry-Perot cavity with one plane mirror and one concave mirror. The plane mirror was mounted on a piezoelectric transducer (PZT) to scan the cavity modes when needed. The cavity body was made of fused silica, a material with low thermal expansion coefficient. The 20-cm cavity length gave a free spectral range of 750 MHz. The typical Pound-Drever-Hall (PDH) technique[15] was employed to lock the laser frequency to the reference cavity, as shown in Fig. 2. A 20-dBm radio frequency (RF) field with a frequency of 22 MHz was applied to an electro-optic modulator (EOM) through a resonator, which produced a modulation depth of 1 measured as the intensity ratio of a first-order sideband and carrier. The reflection signal of the cavity was detected by a high-speed photodetector (Hamamatsu, S5971) and then sent to a phase-sensitive detector (Mini-Circuits, SYPD-1) to produce the desired PDH error signal (see Fig. 3). The full-width at half-maximum (FWHM) of the transmission peak was measured to be 2.4 MHz, corresponding to a finesse of 310.

Feedback to the laser was applied by a fast loop and a slow loop, respectively. The proportion error signal was sent directly to the fast modulation input (bandwidth of

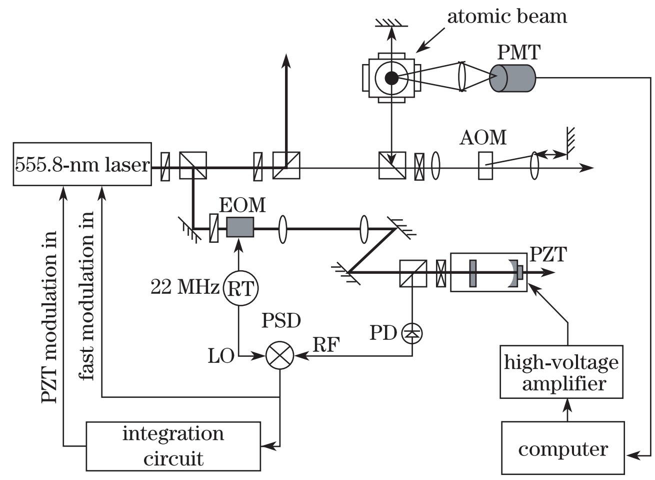

Fig. 2. Schematic of the frequency stabilization of the 556-nm laser. LO: local oscillator; PSD: phase-sensitive detector; PD: photodetector; AOM: acousto-optic modulator.

1 kHz) of the fiber laser, serving as the fast feedback. At the locking point, the error signal had a slope of 0.25 V/MHz, which was deduced from the curve in the inset of Fig. 4. An integrated error signal was applied to the PZT modulation input of the fiber laser driver, serving as the slow feedback. At the locking state, the frequency fluctuation can be monitored by the error signal, as shown in Fig. 4. The error signal had a value of about 25 mV, indicating that the linewidth must be less than 100 kHz, which was also smaller than the natural linewidth of the intercombination transition.

To reduce the long-term frequency drift of the cavity mode, the cavity was placed in an aluminum chamber with two anti-reflection (AR) coated glass windows. This chamber was wrapped by heating films and was temperature controlled to a stability of 10 mK. The cavity was supported by four teflon rods to avoid direct thermal contact with the chamber. Even so, a drift of approximately 10 MHz was still observed in just half an hour. To suppress the slow drift, the laser frequency had to be referenced to an optical transition line of the Yb atoms. For this purpose, we constructed an Yb oven to generate a collimated Yb atomic beam. The oven was heated to a temperature of 450 °C to produce a sufficient atomic flux. Figure 2 shows the schematic of the whole locking system. One probe beam was frequency shifted through an acousto-optic modulator (AOM) double-pass arrangement, so its frequency could be scanned through the AOM driven by a home-made direct digital synthesis (DDS) RF source. The probe beam was then guided to cross the atomic beam at a right angle, and the resonant fluorescence of the ^{174}Yb isotope was collected by an optical lens and detected by a photomultiplier tube (PMT). The FWHM of the fluorescence peak was estimated to be 9 MHz, which was much wider than the natural linewidth due to the divergence of the atomic beam. A trigger signal from a computer was used as the timing of the servo system. Frequency scan was performed when the trigger signal was at high-voltage state. The frequency of the RF source was linearly ramped from 70 to 90 MHz over a time of 100 ms, which corresponded to a 40-MHz scan range of the laser frequency. The fluorescence signal from

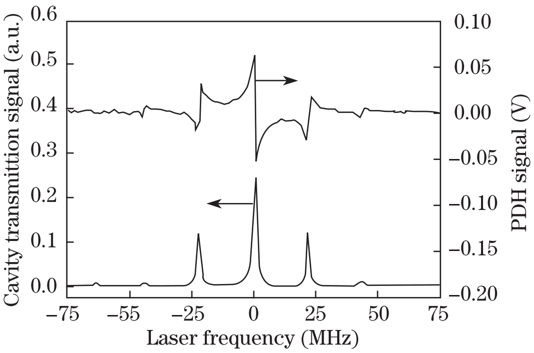

Fig. 3. PDH signal (upper curve) and cavity transmission signal (lower curve) as the laser light is frequency scanned across a cavity mode. The laser is phase modulated with a frequency of 22 MHz and a modulation depth of 1. The FWHM of the transmission peaks is 2.4 MHz, which corresponds to a finesse of 310.

the PMT was recorded by the computer at the same time. Compared with the FWHM of the fluorescence peak, this much larger scan range can certainly cover the whole peak.

At the low-voltage state of the trigger signal, the frequency was set to the initial point (70 MHz), waiting for the next scan. The fluorescence peak was fitted with a Gaussian profile to determine the peak position. The error signal was deduced from the difference between the measured value and the initial one at the setting point (80 MHz), and was then sent to an integration circuit with an integration time of 3 s, yielding a feedback signal. After amplification, this feedback signal was eventually applied to the PZT of the cavity in order to compensate for the long-term drift. The servo cycle was repeated four times per second, as controlled by a computer.

We successfully suppressed the long-term drift of the laser frequency to be within 50 kHz in more than 5 h, as shown in Fig. 5. To filter and eliminate the fast fluctuation in the error signal, each data point in Fig. 5 is actually an averaged value over a time of 3 s. The inset displays a typical frequency drift within 1 h. The locking is very stable and robust. Even if the probe beam is blocked for several minutes, the laser can quickly be

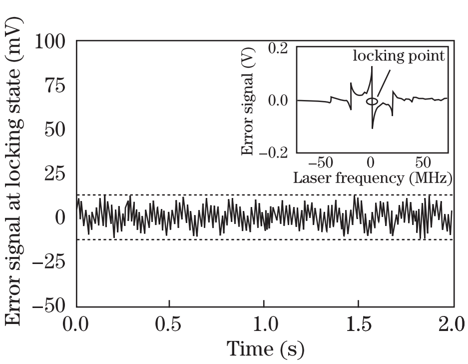

Fig. 4. Short-term frequency fluctuation of the 556-nm laser when locked to the reference cavity. The error signal (solid curve) has a value of about 25 mV marked by the dashed lines, indicating that the linewidth must be less than 100 kHz. Note that the error signal has a frequency sensitivity of 0.25 V/MHz at the locking point as shown by the curve in the inset.

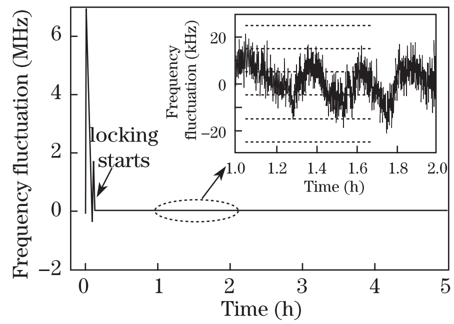

Fig. 5. Long-term frequency drift of the 556-nm laser at locking state. The error signal is averaged for 3 s to filter the fast frequency fluctuation. Inset shows the enlarged portion of the error signal within 1 h, showing a frequency drift within a range of less than 50 kHz.

restored to the original frequency due to the temperature stability of the cavity. Usually, the laser can be locked for a whole night without adjustment, providing a reliable light source for both the laser cooling and photoassociation of Yb.

The systematic errors of frequency locking are mainly due to the fluctuation of the probe power, ambient stray magnetic field, impure polarization of the probe light, imperfect optical alignment, and instability of the atomic flux. Among them, power fluctuation is the most significant factor which may reduce the accuracy in the calculation of the fluorescence peak center. Therefore, the power stabilization of the probe light is also included in our system (not shown in Fig. 2), and this is reduced to less than 1%. The ambient stray magnetic field should cause a fluorescence peak to split into σ^+ and σ^-components. If the splitting is much less than the peak width, the two components are actually overlapped and do not affect the determination of the peak position. In our condition, the ambient stray magnetic field is less than 1 Gs, and we did not observe a noticeable splitting. On the other hand, we used a linearly polarized probe light, so the symmetric splitting of the σ^+ and σ^- components did not shift the peak center. An impure linear polarization will evidently make the peak look deformed and shifted. To avoid this problem, we used a Glan-Taylor polarizer with a high extinction ratio of 10^5 to ensure a pure linear polarization. An imperfect alignment between the probe light and the atomic beam will lead to the Doppler shift of the fluorescence peak. In our configuration, the probe light crosses the atomic beam at a right angle and then goes back the same way. The residual Doppler shifts in two directions are roughly balanced so that the fluorescence peak has no shift in frequency except a slight broadening. The short-term instability of the atomic flux is inevitable, but its effect can be canceled by the integration circuit.

In conclusion, using single-pass SHG in a PPLN crystal, we have obtained a 556-nm laser light operating at the intercombination transition of Yb. Furthermore, we have realized the robust frequency locking of this laser, and a frequency stability better than 100 kHz is reached, which is well below the natural linewidth of the intercombination line. The short-term frequency fluctuation is suppressed by locking the laser to a reference cavity, whereas the long-term frequency drift is feedback controlled as the laser frequency is referenced to a fluorescence peak of an excited atomic beam. The long-term frequency drift is finally reduced to be less than 50 kHz. This method prove to be very robust and can also be extended to other alkaline-earth-metal atoms.

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