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Development of a frequency-stabilized 555.8-nm laser

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Experiments on developing a frequency-stabilized 555.8-nm laser are presented. The 555.8-nm laser is obtained by frequency doubling of a 1111.6-nm diode laser through single-passing a periodically poled lithium niobate (PPLN) waveguide. The 555.8-nm laser is then locked to a stable high-finesse Fabry–Perot (FP) cavity by the Pound–Drever–Hall (PDH) technique. The finesse of the cavity is measured by the heterodyne cavity ring-down spectroscopy technique. The linewidth of the 555.8-nm laser is investigated. After the laser is locked, the laser line width is reduced to about 3 kHz. This frequency-stabilized 555.8-nm laser is used in experiments on the laser cooling and trapping of ytterbium atoms to develop an ytterbium optical clock.

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Frequency-stabilized light sources are essential in a wide range of applications, such as atomic clocks, gravitational-wave detection, and quantum information processing[1–3]. Significant efforts have recently been made to improve the performance of optical atomic clocks and achieve the recommended accuracy of $10^{-18}$[4–7]. In an ytterbium optical atomic clock, second-stage cooling relying on the 555.8-nm $^{1}S_{0} - ^{3}P_{1}$ transition must be performed after the broadband 399-nm $^{1}S_{0} - ^{3}P_{1}$ cooling process so that the atoms can be cooled down to the microkelvin level, which is adequately cold for loading atoms efficiently into the optical lattices. Given that this intercombination transition has a natural linewidth of 182 kHz, a frequency-stabilized laser with a much narrower linewidth is required for second-stage cooling. To the best of our knowledge, stable 555.8-nm light sources have been developed by locking to an external cavity[8,9], an ytterbium atomic transition[10,11], or a phase-locked fiber comb[12].

In this letter, we report experiments on developing a frequency-stabilized 555.8-nm laser system forming part of a $^{171}$Yb optical lattice clock. The 555.8-nm laser is frequency stabilized to a high-finesse Fabry–Perot (FP) cavity by the Pound–Drever–Hall (PDH) technique to reduce the laser linewidth to about 3 kHz. The proposed frequency-stabilized 555.8-nm laser system is successfully used in the laser cooling and trapping of ytterbium atoms in an $^{171}$Yb optical clock and may be applied for building $^{174}$Yb optical clocks.

The 555.8-nm light is generated by the second harmonic generation (SHG) of a 1111.6-nm laser, as shown in Fig. 1. A periodically poled lithium niobate (PPLN) waveguide is used for frequency doubling. A 1111.6-nm diode laser (DL Pro, Toptica Photonics AG, Germany) with a linewidth of 1 MHz is injected into a fiber amplifier (Keopsys Inc, French) through a fiber. The power-amplified 1111.6-nm laser is then inputted directly into the waveguide through the fiber connection. The PPLN crystal is held in a temperature controlled oven (LDT-5525B, ILX Lightwave Corp, USA) with an uncertainty of 0.1 °C.

A high-finesse FP cavity (ATFilms Inc, USA) is used to stabilize the frequency of the 555.8-nm laser. The linear cavity consists of two high-reflectivity mirrors optically connected by a 10-cm-long spacer entirely made of ultra-low expansion material. It is a half-symmetric resonator constructed from a plane mirror and a 50-cm radius concave mirror. The free spectral range (FSR) of the cavity is 1.5 GHz. The cavity is placed horizontally inside a vacuum chamber ($\sim 5 \times 10^{-5}$ Torr) pumped by an ion pump, and the cavity temperature is stabilized at 22.005 °C with an uncertainty of 0.002 °C.

The PDH locking technique[13,14] is utilized to stabilize the frequency of the 555.8-nm laser. A schematic of the experimental setup is shown in Fig. 1. Using a $\lambda / 2$ waveplate and a polarizing beam splitter (PBS1), part of the 555.8-nm laser is sent to the frequency-locking system. The laser firstly goes through a double-pass

![Fig. 1. (Color online) Schematic of the experimental setup. A waveguide (WG) is used for second harmonic generation. The high-finesse Fabry Perot (FP) cavity is used to lock the laser frequency. DL: diode laser; FA: fiber amplifier; FMS: fiber mating sleeve; TC: temperature controller; $\lambda / 2(\lambda / 4)$: half (quarter) waveplate; PBS: polarizing beam splitter; L (M): lens (mirror); AOM (EOM): acousto-optic (electro-optic) modulator; AMP: radio frequency amplifier; DBM: double-balanced mixer; PS: phase shifter; PD: photodetector; PMT: photomultiplier tube.](image-url)
The resonant transition frequency as closely as possible by manually adjusting the PZT voltage of the 1111.6-nm diode laser. The fluorescence signal corresponding to the transition $^{1}S_{0}(F=1/2)\rightarrow^{3}P_{1}(F'=3/2)$ can be obtained by electronically scanning the PZT voltage of the 1111.6-nm diode laser and looking for the fluorescence signals with the PMT. Furthermore, one cavity mode is allowed close to the fluorescence-signal peak of the transition $^{1}S_{0}(F=1/2)\rightarrow^{3}P_{1}(F'=3/2)$ by adjusting the RF frequencies of AOM1 and AOM2. Finally, the 555.8-nm laser frequency is locked to this typical cavity mode. The third part of the 555.8-nm laser is also firstly sent through the double-pass AOM3 with a RF frequency of 80 MHz and then delivered to the 555.8-nm magneto-optic trap (MOT) for cooling and trapping ytterbium atoms; its frequency detuning is controlled by the AOM3, as shown in Fig. 1. The linear frequency drift of the FP cavity can be cancelled by tuning the AOM1 frequency before every locking process. In experiments with intervals of one week, the cavity drift is at most 200 kHz. For daily experiments, manual correction is unnecessary.

Figure 2 shows the dependence of the SHG output power on the fundamental power. The conversion efficiency decreases when the fundamental power is over 120 mW. As mentioned in our previous theoretical work$^{[15]}$, high fundamental light intensities result in thermally induced dephasing effects and nonlinear absorption, which may be main factors influencing conversion efficiency degradation of a waveguide. Given that the SHG output power is sensitive to the crystal temperature because of the phase matching condition, the SHG power is measured as a function of the temperature of the crystal, as shown in the inset of Fig. 2, where the fundamental power is set to about 190 mW.

The plot of the 555.8-nm laser output power as a function of crystal temperature shows typical sinc$^2$ function behavior. The measured full width at half maximum of the center peak is about 1.3 °C, and the optimal temperature where the 555.8-nm laser output power is maximized is 36.8 °C. A temperature stability of 0.1 °C around the optimal temperature controls the fluctuations of the SHG output power to less than 0.3%. Given that the input power of the 1111.6-nm laser cannot exceed the threshold of 0.3 mW, the ytterbium atomic beam effuses from an oven heated at a temperature of 380 °C. A photomultiplier tube (PMT) is perpendicularly mounted above this interaction area to observe fluorescence signals.

In the experiment, a wavemeter is firstly used to measure the frequency of the 555.8-nm laser, after which the frequency of the 555.8-nm laser is allowed to approach the resonant transition frequency as closely as possible by manually adjusting the PZT voltage of the 1111.6-nm diode laser. The fluorescence signal corresponding to the transition $^{1}S_{0}(F=1/2)\rightarrow^{3}P_{1}(F'=3/2)$ can be obtained by electronically scanning the PZT voltage of the 1111.6-nm diode laser and looking for the fluorescence signals with the PMT. Furthermore, one cavity mode is allowed close to the fluorescence-signal peak of the transition $^{1}S_{0}(F=1/2)\rightarrow^{3}P_{1}(F'=3/2)$ by adjusting the RF frequencies of AOM1 and AOM2. Finally, the 555.8-nm laser frequency is locked to this typical cavity mode. The third part of the 555.8-nm laser is also firstly sent through the double-pass AOM3 with a RF frequency of 80 MHz and then delivered to the 555.8-nm magneto-optic trap (MOT) for cooling and trapping ytterbium atoms; its frequency detuning is controlled by the AOM3, as shown in Fig. 1. The linear frequency drift of the FP cavity can be cancelled by tuning the AOM1 frequency before every locking process. In experiments with intervals of one week, the cavity drift is at most 200 kHz. For daily experiments, manual correction is unnecessary.

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The safety value of 200 mW, which is required by the manufacturer, a laser power of about 30 mW at 555.8-nm can be obtained.

The finesse of the FP cavity is measured by the heterodyne cavity ring-down spectroscopy technique\[16\], as shown in Fig. 3. The RF power is not applied on the EOM during this measurement. By rapidly sweeping the PZT of the 1111.6-nm diode laser, the reflection signal detected by PD2 will oscillate with an exponentially decaying envelope. The ring-down time extracted by fitting of the data is about 3 \(\mu\)s, and the finesse of the cavity is estimated to be about 15000.

Figure 4 shows the transmission signals and the PDH error signals before and after the 555.8-nm laser is locked. The inset in Fig. 4 shows the DC component of the reflection signal from the cavity. The reflection signal shows a dip that is never close to zero, which is attributed to the fact that the transmission through the input mirror is not equal to the total loss within the cavity, thereby resulting in low coupling efficiency. Nevertheless, it is less important than minimizing the loss to achieve high finesse in the cavity and obtain high signal-to-noise ratio (SNR) error signals for robust laser frequency stabilization.

To demonstrate that the laser is well locked to the \(^1S_0\to\(^3P_1\) transition of the desired ytterbium isotope, fluorescence signals from the PMT are monitored. By finely tuning the frequency of AOM1, the locking point of the PDH error signal is aligned to the peak of the fluorescence signal. When the laser is locked, the PMT signal (not depicted in Fig. 4) stays at the peak of the fluorescence signal. PD1 signal is flat and remains at the peak, as shown in Fig. 4, which indicates that the 555.8-nm laser is resonant with the atomic transition. After the laser is frequency stabilized, the frequency jitter is reduced. By adjusting the frequency of AOM3 relative to that of AOM2, correct frequency detuning of the 555.8-nm laser for laser cooling experiments can be achieved.

Using another similar 555.8-nm laser system, the 555.8-nm laser linewidth can be measured. The second 555.8-nm laser is used in our second series of ytterbium atomic clock experiments and kept perpetually free-running during the measurements; the linewidth of this laser is about 50 kHz. The beatnotes between the two 555.8-nm lasers with and without locking of the original 555.8-nm laser are shown in Figs. 5(a) and (b), respectively. In Fig. 5(a), both lasers are free-running. The beatnote signal shows a \(-3\)-dB linewidth of about 1 MHz at a resolution bandwidth (RBW) of 30 kHz by Lorentzian fitting. In Fig. 5(b), the 555.8-nm laser is locked to the FP cavity, whereas the second 556.8-nm laser remains free-running. In this system, the \(-3\)-dB linewidth is about 36 kHz at a RBW of 30 kHz and Lorentzian fitting. This finding implies that the linewidth of the original 555.8-nm laser is less than 50 kHz, and its frequency jitter is mostly suppressed after frequency stabilization.

The beatnote between the locked 555.8-nm laser and a titanium-sapphire-type frequency comb is measured, as shown in Fig. 5(c). The optical comb is phase-locked to a 1064-nm laser referenced to an ultra-stable FP cavity.
The linewidth of the 1064-nm laser is about 1 Hz, which is transferred to the optical comb. Each frequency component around 555.8-nm has a linewidth of about 1 Hz, which is much narrower than the linewidth of the locked 555.8-nm laser. Figure 5(c) shows that the observed linewidth of the beat signal is about 3 kHz at a RBW of 3 kHz by Lorentzian fitting; thus, the linewidth of the frequency stabilized 555.8-nm laser is about 3 kHz. Given that the natural linewidth of the $^1S_0-^3P_1$ transition of ytterbium atoms is 182 kHz, this laser has adequate properties to achieve second-stage cooling in the Yb atomic clock experiment. The 555.8-nm laser shows frequency instability in the $^{10}_{12}$ level at an average time of 1 s.

In our experiment, the 555.8-nm laser can be locked to the FP cavity for one day. This frequency stabilized 555.8-nm laser may be used to cool and trap ytterbium atoms successfully in the second MOT. Thus, large numbers of cold atoms may be loaded in the optical lattices. The $^1S_0-^3P_0$ clock-transition spectrum of $^{171}$Yb atoms has recently been observed to feature good SNRS, which is very helpful for developing an ytterbium optical clock in our laboratory.

In conclusion, we develop a frequency-stabilized 555.8-nm laser to achieve the second-stage cooling of ytterbium atoms. Using a SHG with the PPLN waveguide, a 555.8-nm laser with an output power of about 30 mW is generated. This laser frequency is then locked to a high-finesse FP cavity, and a linewidth of about 3 kHz is obtained. The proposed system shows excellent results in our ytterbium optical clock experiments.

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