

Recent progress of neutral mercury lattice clock in SIOM

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Abstract. Neutral mercury atom is one of good candidates of optical lattice clock. Due to its large atomic number, mercury atom is insensitive to black body radiation, which is the severe limitation for the development of optical clocks. However, the challenge of neutral mercury lattice clock is the requirement of high power deep-UV lasers, especially for both the cooling laser and the lattice laser. Here, we report the recent progress of neutral mercury lattice clock in SIOM, including the development for laser cooling of mercury atom and the cooling laser system with fiber laser amplifier. We have realized the magneto-optical trap of mercury atoms and measured the parameters of cold mercury atoms. A home-made external cavity diode laser works as a seed laser for a room temperature 1014.8 nm fiber laser amplifier. A new efficient frequency-doubling cavity from 1015 nm to 507 nm has been developed.

1. Introduction

Mercury is the heaviest stable atom that has been laser cooled. Its large nuclear charge number ($Z=80$) is a great advantage for precision measurement of some physical constants, such as permanent electric dipole moment and fine structure constant [1, 2]. With the improved performance of ultra-stable lasers and development of optical frequency comb, optical clocks advanced very quickly. The instability and uncertainty of optical lattice clock has gone to $2 \times 10^{-16}/\sqrt{\tau}$ and 10^{-18} level respectively, which has already surpassed microwave fountain clocks [3-6]. While Sr and Yb optical lattice clock mainly limited by blackbody radiation (BBR) shift, neutral mercury atom is a good candidate for optical lattice clock due to its low sensitivity of BBR at room temperature [7-10], which is no necessary to take a complex system to control the temperature uncertainty or operate under the cryogenic environment. However, the laser source for neutral mercury lattice clock is tough challenging because of their deep-UV region. Especially for cooling and lattice laser, high UV power is required. Here, we report the recent progress of laser cooling for neutral mercury atom and the development of a new laser cooling system in Shanghai Institute of Optics and Fine Mechanics (SIOM).

2. Laser cooling of neutral mercury atoms

An experimental setup of magneto-optical trap (MOT) was established for laser cooling of neutral mercury atoms. It is composed of vacuum system, cooling laser system, imaging system and time sequence control system. We can produce and measure cold mercury atoms in this setup.



2.1. Vacuum system

The vacuum system is consisted of two chambers, a source chamber and a science chamber, which are connected by a gate valve [11]. Source chamber contains a cooled mercury source, which have three main parts: the mercury cup, a heat sink and a multi-stage thermoelectric cooler (TEC). The mercury cup is cooled by the TEC, and the TEC is glued to the water cooled copper heat sink by thermally conductive low outgassing epoxy adhesive (H77, EPO-TEK). For daily operation, the mercury cup cools down to $-70\text{ }^{\circ}\text{C}$ to achieve a high vacuum with 2×10^{-9} Torr. For MOT operation, the temperature is kept at about $-40\text{ }^{\circ}\text{C}$, corresponding to vacuum pressure of about 2×10^{-8} Torr.

The science chamber is a spherical octagonal cavity and it has eight indium-sealed UV fused silica (UVFS) windows with anti-reflection coatings at 254 nm. Six windows are for MOT beam access, and two are for detection and monitoring. The whole system is pumped only by an ion pump and the vacuum pressure can be lower than 10^{-9} Torr finally. A pair of MOT coils is mounted on the science chamber. After the compensation of the residual magnetic field by three pairs of Helmholtz coils, the total residual magnetic field is less than 10 mG in the MOT region.

2.2. Cooling laser system and optical configuration

A commercial frequency quadrupled semiconductor laser (Toptica, TA-FHG-1030) works as the cooling laser, which is locked on the cooling transition by sub-Doppler frequency modulation (FM) spectroscopy [12]. The commercial laser can maximally generate output power of 36 mW after two stages of frequency doubling with LBO and BBO crystals. The UV output laser is split into two beams by a beam splitter. About 10% of the UV laser is used to FM spectroscopy and the rest UV laser goes to the MOT chamber.

Because of the limitation of bandwidth in the servo loop of the frequency doubling, a feed-forward (FF) method is adopted to improve the frequency tunability of the UV laser system. FF module also reduces the laser frequency noise, when the laser frequency is locked on atom spectrum. The enhancement of the tunability and stability of UV laser gives a lot of advantages in the experiments of laser spectroscopy and laser cooling of mercury atom.

The sub-Doppler frequency modulation (FM) spectroscopy is adopted in our experiment. Almost all of the transitions have been found in saturated absorption spectroscopy (SAS) except ^{196}Hg because of its low natural abundance ($\sim 0.6\%$). With a high speed servo controller (New Focus, LB1005), the UV laser can be locked on the FM signals. Figure 1 shows the FM signals and saturated absorption signals for 8 transitions.

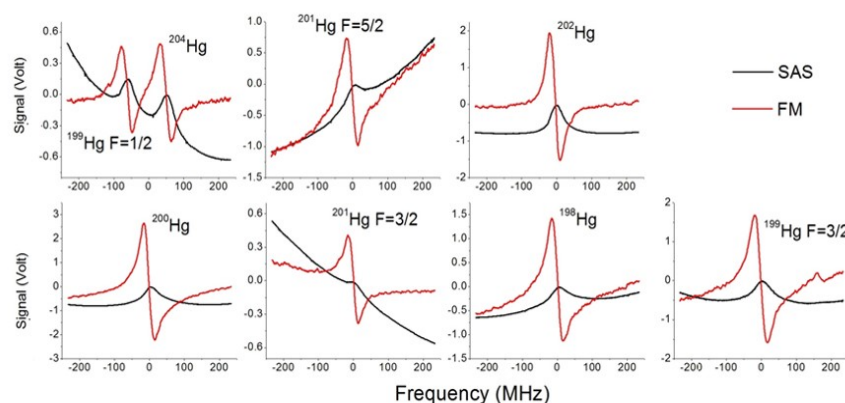


Figure 1. FM spectroscopy for all observed transitions.

Because of the shortage of the UV laser power, we adopt a folded beam configuration with a single shot to replace the normal configuration with six cooling beams for MOT [11]. The cooling laser power is about 10~20 mW and the beam diameter is magnified to 10 mm in the MOT. The MOT signal is detected by an electron multiplying charge coupled device (EMCCD, Andor, iXon3 885DU)

and a photomultiplier (Hamamatsu, H9305-1) through 4f imaging system with fluorescence method. The magnification is 0.5 and the overall photon collection efficiency is about 0.0033.

2.3. Measurement and optimization of cold mercury atom in MOT

We have clearly observed the atom signals for all six rich abundance isotopes and measured the atom numbers by the fluorescence imaging of the cold mercury atoms. Background vapor pressure is an important factor in experiment, which could be changed by the Hg source temperature through TEC current. We measured the atom number of ^{202}Hg at different Hg source temperature as shown in figure 2. We choose $-45\text{ }^{\circ}\text{C}$ as work temperature. The capture rate and stable atom number in MOT is strongly influenced by laser detuning. The relation of the atom number in MOT and the laser detuning is measured for ^{202}Hg atom, as shown in figure 3. Maximal atom number is about 1.7×10^6 at about -10 MHz detuning. Due to the limited power of the UV laser, we can't measure the relation of the atom number and the intensity of cooling laser. Similarly, the maximal atom number is about 1.5×10^6 for ^{199}Hg atom.

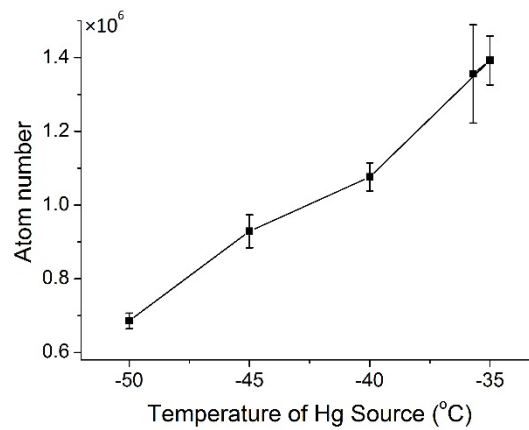


Figure 2. Dependence of atom number and temperature of mercury cup for ^{202}Hg atom.

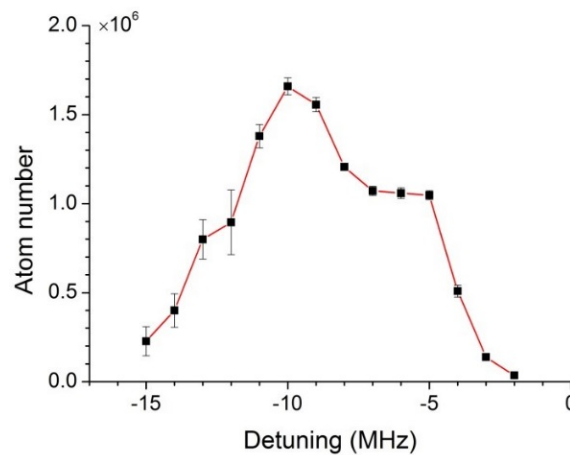


Figure 3. Dependence of atom number and laser detuning for ^{202}Hg atom.

The temperature was measured by time of flight method (TOF). The minimum flight time is 7 ms which is limited by the action of mechanical shutter. Figure 4 shows the TOF pictures at different flight time (left) and fitting result (right). Because of the theory of Doppler cooling, the lowest temperature had to be achieved in small detuning, which conflicted with the maximization of atom

number [13]. So we decrease the laser detuning at the end of MOT loading. The lowest temperature is 170 μK for ^{202}Hg and 50 μK for ^{199}Hg .

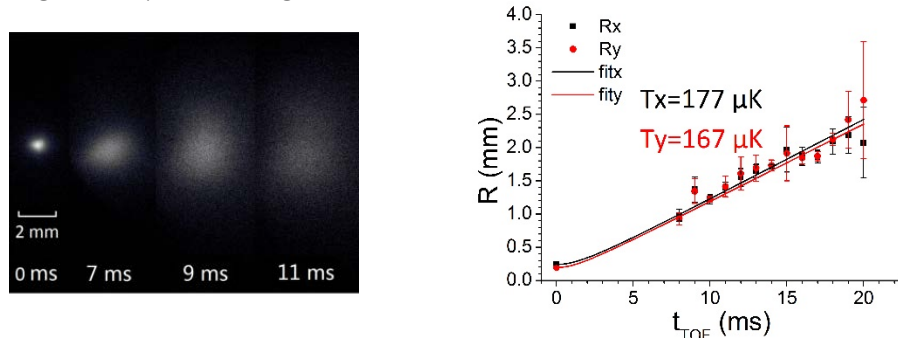


Figure 4. Temperature measurement for ^{202}Hg . Atom images at different TOF time (left) and temperature calculation by fitting result (right).

3. The development of cooling laser system

As mentioned above, to establish a neutral mercury optical lattice clock, the most challenging thing is to generate a high power deep UV laser at 253.7 nm for laser cooling of neutral mercury atom. In our previous work, we developed a 1014.8 nm fiber laser amplifier with short polarization-maintaining Yb-doped single mode fiber, which can work at room temperature [14]. But only 75 mW UV laser is generated at 4 W input IR laser power with two commercial doubling cavities. Here we present our recent development of cooling laser system.

3.1. The design of cooling laser system

The schematic diagram of our cooling laser system is shown in figure 5. A home-made external cavity diode laser (ECDL) works as seed laser for the 1014.8 nm fiber laser amplifier. After a single stage of fiber laser amplifier, the fundamental power can reach 7 W. The first doubling cavity with LBO crystal was completely demonstrated, but the second doubling cavity with BBO crystal is under constructed.

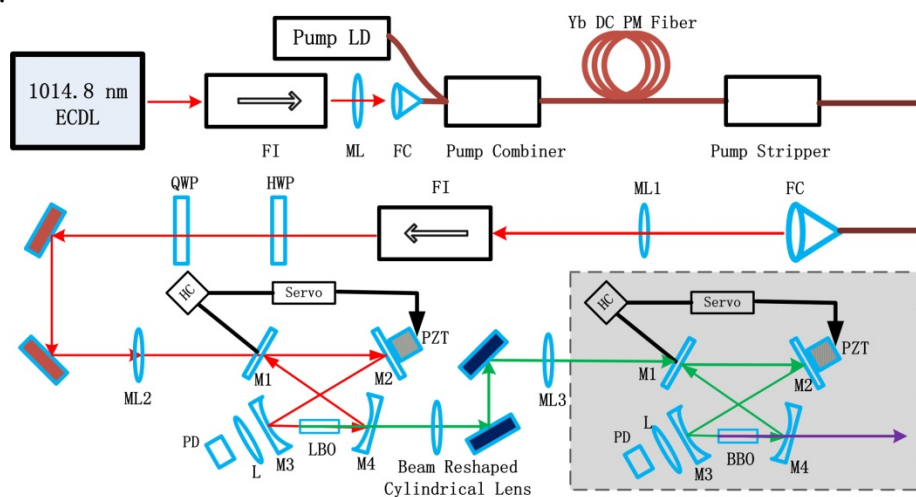


Figure 5. Schematic diagram of cooling laser system. FI, Faraday Isolator; ML, Mode-matching lens; FC, Fiber collimator; Yb DC PM Fiber, Yb Double Clad PM Fiber; HC, Hansch-Couillaud method; PZT, piezoelectric transducer; LBO, lithium triborate; L, lens; PD, photodiode.

3.2. The home-made ECDL

A home-made external cavity diode laser at 1014.8 nm is made as seed laser. The ECDL adopted Littrow configuration with an AR-coated laser diode (EYP-RWE-1060, Eagleyard) and 1200 lines/mm

grating with 30% diffraction efficiency at 1015 nm. The output power is about 45 mW, and the typical line width is about one hundred of kHz. Its ASE suppression ratio is about 55 dB which even better than our used commercial laser (DL pro, Toptica), as shown in figure 6. After an optical isolator, the laser is coupled into a PM single mode fiber (PM 980) with laser power of 20 mW, which is sufficient for the 1014.8 nm fiber laser amplifier.

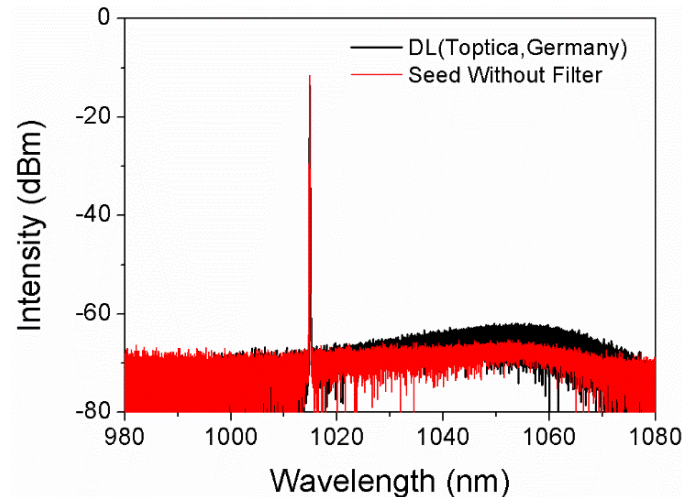


Figure 6. The comparison of ASE between the home-made ECDL (red) and the commercial ECDL (DL pro, Toptica) (black). The ASE of the home-made ECDL is about 10 dBm lower than the commercial ECDL at 1050 nm.

3.3. The 1014.8 nm fiber laser amplifier at room temperature

The fiber laser amplifier is same as Ref. [14], but the power of seed laser is much lower. When it operated at high output power, self-excitation will existed. Due to this reason, we insert a bandpass filter (FF01-935/170-25, Semrock) to purify the spectrum around 1030 nm. Now the maximal output power is 7 W, which limited by the current supply of pump laser, and the corresponding ASE suppression ratio is about 45 dB, as shown in figure 7.

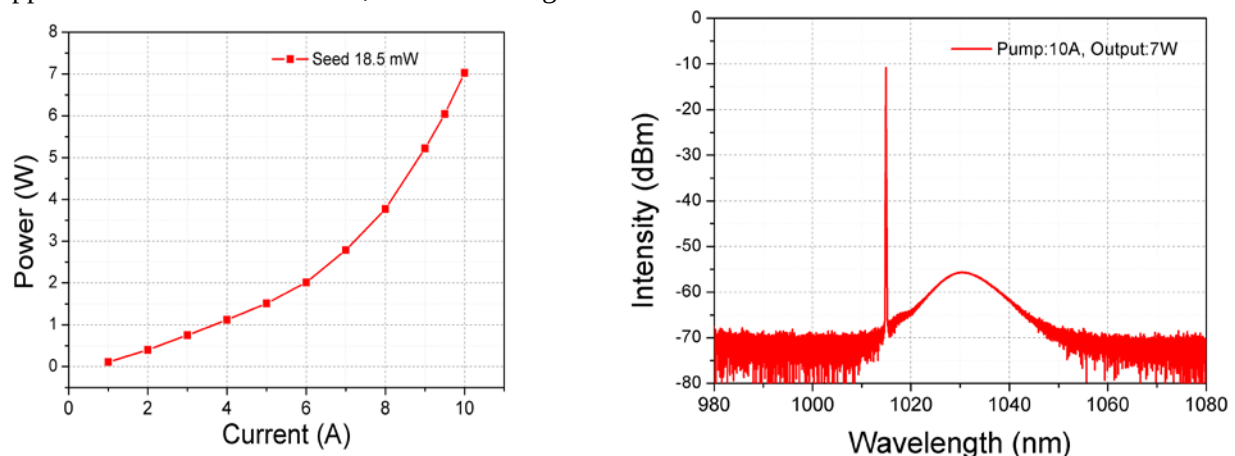


Figure 7. The output features of the 1014.8 nm fiber laser amplifier. The left figure is the relation of the output power and current of pump diode, and the right figure is the spectrum measurement at 7 W output power.

3.4. The first doubling cavity with LBO crystal

The high conversion efficiency and high stability from IR fundamental laser (1014.8 nm) to green laser (507.4 nm) is crucial to generate high power cooling laser in UV. A bow-tie ring cavity is adopted with a 20 mm length AR-coated LBO crystal, as shown in figure 5. The beam waist of IR

TEM₀₀ mode is about 45 μm at the center of LBO crystal, and the transmissivity of input coupler is about 3% around 1014.8 nm. Two lenses are used to match the mode of laser beam from fiber collimator and the fundamental mode of doubling cavity with high efficient of about 98%. The doubling cavity is locked by Hansch-Couillaud method [15]. The maximal output power of green laser is about 3.0 W at 4.9 W input power of IR laser with conversion efficiency of 61%, as shown in figure 8. The performance of this doubling cavity is well agreed with our design and calculation.

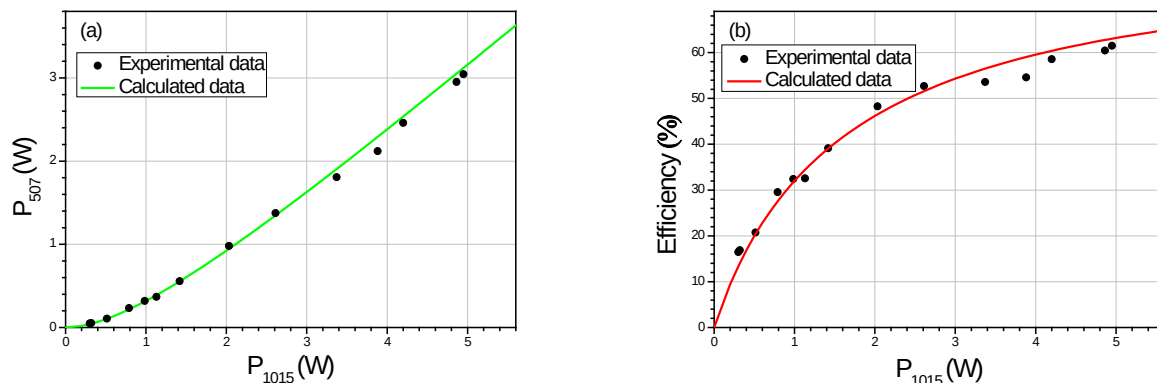


Figure 8. The performance of first doubling cavity. (a) The output power of green laser versus the input power of IR laser. (b) The conversion efficiency versus the input power of IR laser. The green (red) line is given by theoretical calculation.

4. Conclusions

In conclusion, we established an experimental system for laser cooling of neutral mercury atom, and successfully trapped six mercury isotopes in the magneto-optical trap. The atom number is about 1.7×10^6 for ^{202}Hg and 1.5×10^6 for ^{199}Hg atom. The temperature is about 170 μK for ^{202}Hg and 50 μK for ^{199}Hg . To enhance the laser power, a 1014.8 nm fiber laser amplifier was developed, which can work at room temperature. With our new develop of cooling laser system, the maximal output power at 507 nm is about 3 W. These works laid a good foundation to realize the neutral mercury lattice clock.

5. Acknowledgement

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