A calcium vapor cell for atomic spectroscopy

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A calcium vapor cell used in laser spectroscopy usually suffers from calcium coating on the cell windows. To solve the problem, we add two mirrors in the cell to reflect the laser beam, then the calcium will coat on these mirrors instead of on the windows. Calcium coating degrades the reflectivity of the mirrors at the beginning, but the mirrors become calcium mirrors after a certain period of coating and their reflectivity will not change by further calcium coating. Using this cell in a conventional saturated-absorption spectroscopy, the observed saturated-absorption peak at 657 nm is about 2.4% of the probe beam power and its linewidth is below 300 kHz. Therefore, a portable secondary calcium-wavelength standard at 657 nm having an accuracy better than 1×10^{-11} is possible. In addition, our cell has a continuous working time longer than 3 d and it can be easily extended to 10 d. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1511800]

I. INTRODUCTION

Diode lasers at about 650 nm are frequently used in applications of optical storage, such as a DVD player; thanks to mass production, they have higher power, better quality, and lower cost than diode lasers at 635 nm. Those diode lasers could be the ideal light sources of wavelength-stabilized lasers for laser interferometers if their wavelengths can be traced to a recommended radiation. A recently adopted recommended radiation at 657.46 nm[1] is suitable for this wavelength trace. The relative uncertainty of the wavelength can reach 6×10^{-13} if the laser wavelength is locked to the $^{1}S_{0} - {}^{3}P_{1}$; $\Delta m_{J} = 0$ transition of laser-cooled calcium atoms.[2,3] Although the accuracy of this wavelength is very high, the system is very complicated and bulky. It is not easy for intercomparison between laboratories. From this point of view, building a portable and compact size Ca-stabilized laser system as the secondary standard of the recommended radiation is an important issue for application of the above-mentioned standard even though its accuracy is adequately degraded.

Saturation spectroscopy[4] using a simple vapor cell is a convenient basis to build a compact wavelength-stabilized laser system. However, it is not suitable for calcium, because the vapor pressure of calcium at room temperature is too low to observe the spectroscopic signal. To generate sufficient vapor pressure, calcium should be heated in a vacuum environment to a temperature higher than 400 °C. At such a high temperature, calcium atoms will coat the optical windows of the cell, and the pump and probe laser beams that go through the windows will be blocked. A heat pipe, using a heating boat to heat the calcium and a buffer gas to prevent the

reaction between the calcium atoms and the cell windows, solves the problem with the cost of considerable pressure broadening caused by the buffer gas.[5] An alternative approach is to use a thermal calcium beam.[6] There is no buffer gas and the laser beam goes across the thermal calcium beam perpendicularly. This prevents the optical windows from being coated by calcium; but the signal-to-noise ratio of the spectrum is low because only limited atoms act with laser light. A NIST group has developed a beam cell[7] that generated a high flux calcium–atomic beam by using many parallel thermal beams orthogonal to the laser beams. The beam cell significantly improved the signal-to-noise ratio of the spectrum, but its operating time for one fill of calcium was only 15 h. Therefore, to design a calcium cell that has long operating time and good signal-to-noise ratio is an important issue for a compact secondary wavelength standard at 657 nm.

Difficulty in constructing a calcium vapor cell is the calcium-coating problem of cell windows and also the loss of calcium atoms too quickly. To reduce the calcium loss rate, a vapor cell with a large diameter tube was used as the calcium container having two small holes at both ends of the tube.
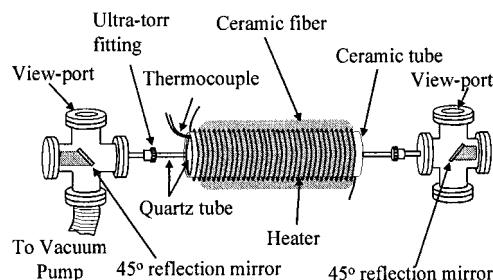

FIG. 1. Schematic diagram of the calcium vapor cell. The two 45° reflection mirrors reflected the laser beam into the calcium cell and kept the vacuum windows clear.

This reduced the rate of atoms escaping from the cell. To solve the calcium-coating problem, we used two reflection mirrors tilted at 45° from the cell axis behind the two holes of the vapor cell. By those mirrors, the laser beams go into the vacuum environment from a view port are deflected 90° and then enter the calcium cell. As the cell was heated, calcium atoms escaped from the holes deposited on the 45° reflection mirrors, and blocked the laser beams until the calcium film on the mirrors was thick enough to form calcium mirrors; then the laser beams could be reflected again. A similar calcium mirror technique has been used in a laser-cooled calcium system.[3] After the mirrors are coated, the cell works like a conventional vapor cell. With this new cell, the working time is much longer than a beam cell. The number density of the calcium atoms is similar to that of a beam cell, and the signal-to-noise ratio of the spectrum is also similar.

II. EXPERIMENTAL SET-UP

A schematic of our calcium cell is shown in Fig. 1. Its main body was a 300 mm long quartz tube 20 mm in diameter and 1.5 mm in wall thickness. Two coaxial 7 mm diam, 60 mm long tubes were fused to both ends of the main body to confine the calcium atoms. The main body of the cell was enclosed in a ceramic tube wrapped with a wire heater and then covered with ceramic fiber for thermal isolation. A thermocouple was inserted between the main body and the ceramic tube to monitor the cell temperature. The temperature of the main body could reach 460 °C by supplying 150 W power to the heater. After filling calcium in the main body, the cell was connected to two four-way crosses by Ultra-Torr fittings. Inside the four-way crosses were two elliptical shaped plane aluminum mirrors. The aluminum mirror could be replaced by a glass plate without any coating, but it was convenient to use it for laser beam alignment before calcium coating and to observe the reflectivity variation from the original aluminum coating to the final calcium coating. The mirrors were at 45° with respect to the axis of the cell; the mirrors changed the propagation direction of the laser beam by 90°. The vapor cell was evacuated by a turbo-pump. The pressure could reach only 5×10^{-2} Pa, which was limited by the Convectron gauge used in our experiment.

The vapor cell could be heated and used for laser spectroscopy for a few hours until the mirrors began to be coated with calcium. After the coating was completed, it acted like a cell with two calcium mirrors. To investigate the coating procedure of the calcium mirrors, we monitored the transmitted laser power after the cell in real time while the cell was heated. The transmitted power was constant for a few hours at 460 °C cell temperature until the calcium coating started. To speed up the calcium coating, we raised the cell temperature from 460 to 600 °C. As the transmitted power dropped down from its original 5 to 4 mW by coating, we began to record the power level every 15 s until the coating procedure was completed.

Using the calcium coated vapor cell, we observed the saturated-absorption spectrum of calcium at 657 nm. The optical arrangement of our saturated-absorption system is shown in Fig. 2. The light source was an extended cavity
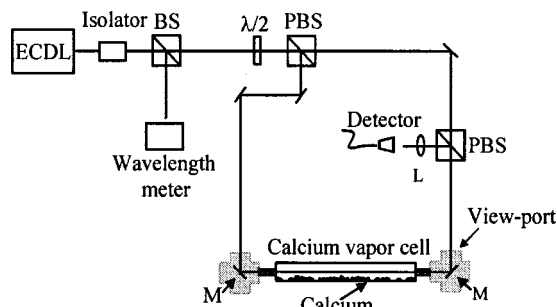

FIG. 2. Optical setup for the saturated-absorption system. Here, the wavelength meter was used to tune the laser frequency to the calcium absorption: ECDL, (BS) beam splitter, PBS, (L) lens, (M) mirror, and (λ/2) half wave plate.

diode laser (ECDL) at 657 nm. Its frequency was tuned by moving the feedback mirror of the laser by a piezoelectric transducer (PZT) and the linewidth was 100 kHz at 50 ms according to the manufacturer's specifications. After an optical isolator the laser light was divided into pump and probe beams by a polarizing beam splitter (PBS). A half wave plate (λ/2) placed before the PBS was used to adjust the power ratio of the pump and probe beams. The power of the pump beam was 0.9 mW and the probe beam was 0.1 mW. The pump and probe beams were aligned to counterpropagate in the cell. The laser beam size was about 2.5 mm×0.7 mm at the center of the calcium cell. Finally, the probe beam was reflected by another PBS and collected into a photodetector by a lens (L). The absorption spectrum was displayed on an oscilloscope while the laser frequency was tuned.

III. RESULTS

In Fig. 3, the transmitted power level before the calcium coating was 5 mW, it reached nearly zero (0.17 mW) in 10 min, and then increased to 4.38 mW, about 87% of the transmitted power level before calcium coating. The original aluminum mirror had a reflectivity of 90%. Because there were two mirrors in the cell, the reflectivity of each calcium-coated mirror was about 84%.

Using this cell, we first observed the Doppler-broadened spectrum of the calcium vapor and the result is shown in Fig. 4. The absorption dip is about 55% at 460 °C cell temperature. The linewidth is about 1.5 GHz. It is slightly larger than the calculated Doppler linewidth of 1.4 GHz. This is because the thermocouple used to monitor the cell temperature was located at the edge of the tube and the temperature at the
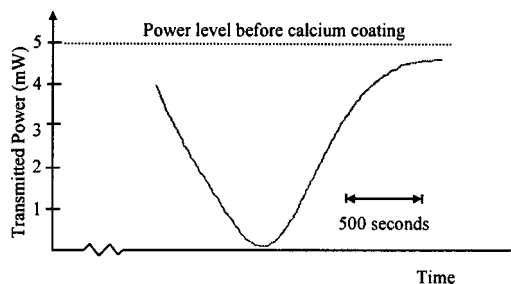

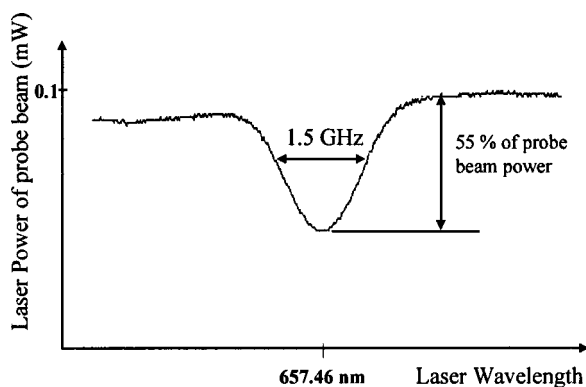FIG. 3. Transmitted power of the probe beam during the calcium coating.

FIG. 4. Doppler-broadened spectrum of calcium observed by our vapor cell. The cell temperature was 460 °C.

central part should be higher. A later measurement showed that the temperature was about 70 °C higher at the center than at the edge.

At the same cell temperature, the saturated-absorption spectrum is shown in Fig. 5 which is taken from an oscilloscope while the laser frequency was tuned by applying a triangular wave to the laser PZT. We could not obtain an averaged spectrum due to a fluctuation of few hundred kHz in the laser frequency at about 1.1 kHz. The three peaks observed in the saturated-absorption spectrum were the three Zeeman components of the calcium $^1S_0-^3P_1$ transition with $\Delta m_J = 0$; $\Delta m_J = \pm 1$, split by the magnetic field from the heating wire. The central peak ($\Delta m_J = 0$) is about 2.7% of the probe beam power. The frequency interval of the Zeeman components of the saturated-absorption spectrum was estimated from the magnetic field strength (0.6 mT) inside the
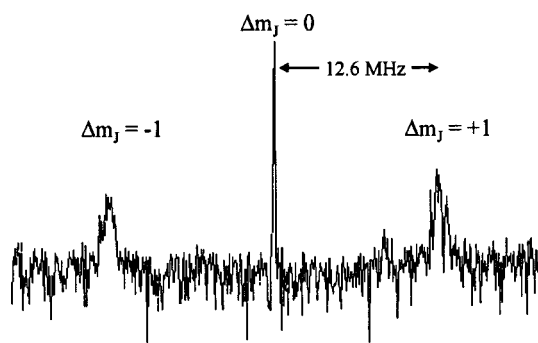

FIG. 5. Saturated-absorption spectrum of calcium observed by our vapor cell. The cell temperature was 460 °C and the magnetic field in the cell was 0.6 mT.

cell and the linear Zeeman shift (21 MHz/mT).[8] The magnetic field was about 1.5 mT at 460 °C cell temperature under normal operation. In order to determine the linewidth accurately, we reduced the heater current temporally. In our situation, the linewidth of the $\Delta m_J = 0$ peak was estimated to be about 230 kHz. The linewidths of $\Delta m_J = \pm 1$ peaks were wider than that of the $\Delta m_J = 0$ peak because the magnetic field was not uniform along the axis of the cell. As for the working time of the cell, we have worked the system continuously for more than 3 d with one fill of calcium.

IV. DISCUSSION

In this article, we report the design of a calcium vapor cell that solved the window-coating problem. The spectroscopic performance for Ca absorption at 657 nm is comparable to the NIST calcium beam cell.[7] The ratio of the saturated-absorption peak to the probe beam power was larger than that of the beam cell.

The most significant factors that limit the accuracy of a laser locked to the saturated-absorption peak of $\Delta m_J = 0$ component using our cell are velocity dependent shifts such as residual Doppler, second-order Doppler, transit, and wave front curvature effects. Other factors that contribute smaller uncertainties included photon recoil (23 kHz splitting), gas lens, quadratic Zeeman (10^8 Hz/T^2), and Stark [1 Hz/(V/cm)^2].[7] These effects will typically limit the accuracy to about 1 kHz.[9] From the present results frequency stability and accuracy better than 1×10^{-11} are possible.

The cell was tested continuously for more than 3 d, and its working time could be easily increased to about 10 d. The optical setup of our saturated-absorption system was still not optimized. It could be improved if we would use an extended cavity diode laser source with additional linewidth reduction. Work along this direction is under investigation now.

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