Development of a stretched absolute wavelength standard using dichroic atomic vapor spectroscopy towards observation of light-induced drift

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Abstract. An absolute wavelength standard broader than the Doppler width of the atomic absorption signal was developed by using a method called dichroic atomic vapor spectroscopy (DAVS). DAVS is known as a method to obtain an error signal for stabilization of laser wavelength, called dichroic atomic vapor laser locking (DAVLL). In the DAVS, a magnetic field is applied to the atomic vapor cell and a stretched signal is obtained by the Zeeman effect. The DAVS experiment was performed by using ring-type permanent magnets and a cesium vapor cell at room temperature, and the placement and number of magnets were optimized. By measuring the height of the DAVS signal calibrated in advance, continuous monitoring of the absolute laser wavelength become possible. The developed system is suitable to be used as a stretched wavelength standard in the experiment of the light-induced drift.

1. Introduction
The radioactive wastes generated in nuclear power generation are planned to be solidified in the glass and disposed at deep underground. However, there are various social problems such as the location determination for the final disposal site and the emission risk due to the long-term storage. The nuclear transmutation of the isotopes with a long half-life is one possibility to reduce the geological disposal. For the transmutation of Cs-135, which is a dominant isotope from the viewpoint of the public exposure, the almost complete isotope separation from Cs-133 is required [1]. However, the efficient separation of Cs isotopes has not been realized because the mass of the Cs isotopes are very close and other properties such as the electronic configurations are almost the same. The isotope separation by the light-induced drift (LID) [2-4] has a possibility to be extended to the industrially effective level because the separation principle works in the thermal equilibrium. The theoretical investigation of the separation of cesium isotopes by LID were performed previously, and resulted in hopeful speculations [5].

In the LID experiment, by optically exciting only the atoms of a certain velocity, the drift velocity is driven by the velocity-selective excitation and the difference of the redistribution speed among the electronic states. For the experiment of the LID, it is necessary to make a wide range absolute wavelength standard because we have to monitor the frequency of the laser to ascertain which atom of the velocity component near the resonant line of cesium is excited by the laser. The drift velocity emerges around ±1 GHz from the center frequency of the target transition and the direction of the velocity is steeply changing around the center frequency. The continuous and stable wavelength standard is required to obtain the dependence of drift velocity on the laser frequency.
Generally, the wavelength standard for laser spectroscopy is created by the atomic transition lines, the interferometer, or combination of them. However, the atomic transition line is stable but not continuous whereas the signal of the interferometer is continuous but hard to be stable. For a stable and continuous wavelength standard, we apply the dichroic atomic vapor spectroscopy (DAVS), which is used for the wavelength stabilization called dichroic atomic vapor laser locking (DAVLL). The works of DAVLL are roughly classified into Doppler DAVLL [6-12] or sub-Doppler DAVLL [13-20]. The sub-Doppler DAVLL has the advantage of locking the frequency inside the narrow region. In the present study, only the Doppler version of DAVS was utilized because the signal over the broad frequency range was important. The similar interest for the wide range signal creation was presented recently [21]. The DAVS provides us the time-stable signal at room temperature by a relatively simple experimental apparatus. In this study, the signal of DAVS was created by using ring-shaped permanent magnets and cesium vapor cell. Since the width of the DAVS signal can be changed by the intensity of the magnetic field and how to use the magnets, the conditions of the magnet arrangement were optimized to be used as a wide range absolute wavelength standard.

2. Experiment

Figure 1. The schematic of the DAVS signal creation (a) and the experimental system (b). HWP, QWP, and PBS mean half-wave plate, quarter-wave plate, and polarizing beam splitter, respectively.

2.1. Principle

The DAVS is often used for making a reference error signal for wavelength stabilization of diode lasers. The laser locking using DAVS has an advantage for providing absolute wavelength reference, stability for temperature change and high-speed feedback because of no need for lock-in amplification. In addition, we made use of the feature of the shape of the DAVS signal broadened around a few GHz. Figure 1 (a) shows the principle of the DAVS signal creation. Under the magnetic field, the transition wavelengths of cesium atoms are separated and shifted by the Zeeman-effect. The direction of the shifts depends on the circularly-polarized component of the laser. Because the linearly polarized light is expressed by the linear combination of the circularly-polarized lights which have opposite chiralities, both shifts are simultaneously observed by the linearly-polarized laser. By using the quarter-wave plate,
the transmitted light intensity ratio of the circularly-polarizing components is transferred to the ratio of horizontally and vertically polarizing components, which can be easily separated by the polarizing beam splitter. The DAVS signal is composed by the difference of two signals given by each polarizing component.

2.2. Experimental apparatus

Figure 1 (b) is the schematic of the experiment. A distributed feedback laser diode (LD-0852-0150-DFB-1, Toptica) was mounted on the TO-3 laser mount (246, Arroyo Instruments) connected to the current and temperature controller (6305, Arroyo Instruments). The wavelength of the laser was scanned by modulating the injecting current using a function generator (WF1974, NF Corporation). The optical isolator (IOT-5-850-MP, Thorlabs) was used to prevent the back reflection causing the instability of wavelength. The power of the laser was attenuated by a pair of the half-wave plate and the polarizing beam splitter. The linearly-polarized laser was inserted into the cesium gas cell composed of Pyrex (length of 100 mm and diameter of 30 mm, Horizon). To generate the magnetic field, the ring-shaped permanent magnets (thickness of 8 mm) were used. The average magnetic field strength of one magnet measured in the center of the ring was 356.5 Gauss. The output from the cell was separated into the two components by a polarizing beam splitter after the quarter-wave plate that transfers the ratio of circular-polarization into the ratio of horizontal and vertical linear polarization. The DAVS signal was generated by measuring the intensity of two components with a balanced amplified photodetector (PDB410A, Thorlabs). A plano-convex lens with a focal length of 150 mm is used to focus the laser into the detector.

The DAVS signal is obtained on the oscilloscope (TDS 8204, Owon) with the signal of a Fabry-Perot Interferometer (FPI 100-0750, Toptica photonics, FSR: 1.0 GHz) for relative frequency calibration.

![Figure 2](image)

**Figure 2.** An example of the absorption signal of the cesium atoms without ring magnets (a), examples of the DAVS signal depending on the position of four ring-shaped magnets (b). Inset illustrations are examples of how to place 4 magnets. The upper shows a DAVS signal when the magnets arranged at equal intervals, and the lower shows those are arranged non-uniformly.
3. Results and discussion

Figure 2(a) shows an absorption signal of cesium atoms in the region of D$_2$ line. In this region, two peaks given by the hyperfine splitting of the ground state are observed. Each peak involves some transitions given by the hyperfine splitting of the excited state.

Figure 2(b) shows an example of the DAVS signal depending on the position of four magnets. If the magnets are put around the center without the spacer between each pair, the DAVS signal did not exhibit the single slope structure ideal for the wavelength reference. This is because the direction of the magnetic field varies inside the cell. The magnetic fields inside the center hole of the ring magnet and outside it are opposite, resulting in the unwanted splitting of the cesium signal due to the variation of the magnetic field. If the magnets were placed at both ends of the cell and nearly even spaces for others, the single slope structure was obtained because the direction of the magnetic field is nearly the same inside the cell in this case.

![Figure 3](image)

**Figure 3.** The DAVS signals obtained by varying the number of ring magnets.

Figure 3 shows the variation of the DAVS spectra depending on the number of ring magnets. The magnets were placed with nearly even spacing. The width of the slope signal got wider with increasing the number of magnets until 10 and started to decrease gradually. With 10 magnets, the cesium cell was just completely covered by the magnets. For more than 11 magnets, the magnets are stuck out. The extra magnets worked to decrease the magnetic field inside the cell.

As the wavelength reference, a monotonically increasing signal was obtained over 2 GHz, which is sufficient to be used in the experiment of the LID. Because the DAVS signal is based on the atomic absorption signal, the signal level and the absolute frequency of the laser can be connected with one-to-one correspondence without fluctuation. And that is relatively robust to the temperature change.
4. Conclusion
The monotonically changing in frequency and stable in time absolute wavelength standard was obtained as the signal of the DAVS. To obtain the signal, it was appropriate to place permanent magnets at equal intervals as much as possible around the Cs cell. The width of the slope of the signal was over 2 GHz and was enough larger than the Doppler width of cesium. It can be used for monitoring the wavelength of lasers in the LID experiment in the future.

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