Cesium $6S_{1/2} \rightarrow 8S_{1/2}$ two-photon-transition-stabilized 822.5 nm diode laser

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A cesium $6S_{1/2} \rightarrow 8S_{1/2}$ two-photon-transition (TPT)–stabilized 822.5 nm diode laser is reported for the first time to our knowledge. Allan deviation of 4.4×10^{-13} (60 s) was achieved, and the possible systematic errors were evaluated as smaller than 2 kHz. We demonstrate that the cesium TPT-stabilized diode laser could be a reliable frequency reference at 822.5 nm wavelength. © 2007 Optical Society of America

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Stable optical references are significant for the metrological applications such as high-precision length measurement, high-stable interferometer, or the control of a Fabry–Perot cavity. It would be interesting to combine the features of diode laser and gas cell to build up a convenient frequency or wavelength reference. In particular, an 820 nm frequency reference has the potential to be used for directly controlling the carrier-envelope frequency of the mode-locked Ti:sapphire laser, which is the most popular mode-locked laser in the wavelength regime of 750–950 nm. In this Letter we demonstrate the feasibility of setting up a frequency reference in the wavelength of 822.5 nm by constructing two cesium $6S_{1/2} \rightarrow 8S_{1/2}$ two-photon-transition (TPT)–stabilized diode lasers (CTSDLs). When two laser systems were adjusted to be under similar conditions, the Allan deviation was measured as 4.4×10^{-13} (60 s), namely, $\Delta f = 160$ Hz. We investigated the possible systematic errors on the locking point, including the studies on resettability, light shift, pressure shift, modulation shift, and the discrepancy between linear and circular polarization in light–matter interaction. We quote conservatively the possible systematic error as 2 kHz.

The cesium $6S_{1/2} \rightarrow 8S_{1/2}$ hyperfine transitions were chosen to be the reference of our frequency-stabilized diode laser based on the following facts: (1) The cesium atom has only one naturally occurring isotope, namely ^{133}Cs. Therefore the locking frequency will not be affected by the nearby spectrum of the other isotopes. (2) Under the same cold-finger temperature, the atom density of cesium vapor is larger than that of the other alkali atoms[1] (except for francium). In other words, cesium vapor can yield higher spectral signal-to-noise ratio (S/N), which yields higher frequency stability in laser stabilization. (3) Because there is no linear Zeeman effect for the $S-S$ transition, the locking frequency is not sensitive to the Earth's magnetic field, and the Zeeman shift is quadratically dependent on the magnetic field at low field strength with the value of $0.2\ \mathrm{Hz}/(\mu\mathrm{T})^2$ by the Breit–Rabi formula.[2,3] (4) Cesium $6S_{1/2} \rightarrow 8S_{1/2}$ hyperfine transition possess excellent spectral isolation (>4 GHz separation). (5) The corresponding absolute frequencies had been determined[4] (100 kHz accuracy, by curve fitting). Previously, to our knowledge, only one group[4] studied the spectral features on cesium $6S_{1/2} \rightarrow 8S_{1/2}$ hyperfine transitions by Ti:sapphire laser, while laser stabilization based on the two hyperfine transitions was not reported.

Figure 1 illustrates the block diagram of our experimental setup that implemented two CTSDLs (CTSDL #1, CTSDL #2). A typical extended-cavity diode laser (ECDL #1) was housed inside an alumina box that was carefully designed for minimizing acoustic and vibrational noise. The home-built ECDL system comprised a two-stage temperature-controlled diode laser (Sanyo DL-7032, 100 mW) and a piezoelectric transducer (PZT)–activated grating (1700 grooves/mm) that were compactly assembled within a mirror mount.[5] The overall laser system yielded 40 mW output power with a free-running jitter of around 1.8 MHz, checked by two similar

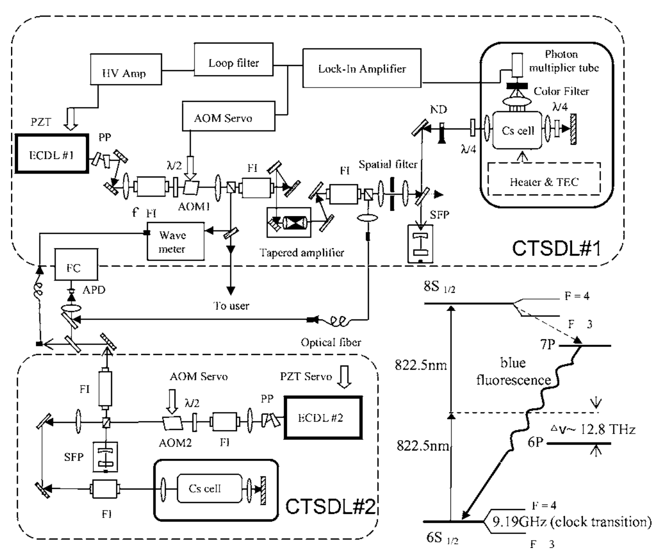

Fig. 1. Block diagram of the experimental setup that implements two CTSDLs with a simplified-level diagram. To save space, the electronic part of CTSDL#2 is omitted because most of the elements are similar to that of CTSDL#1. ECDL, extended-cavity diode laser; PP, prism pair; AOM, acousto-optic modulator; FI, Faraday isolator; SFP, scanning Fabry–Perot; ND, set of neutral density filters; TEC, TE cooler. PZT, piezoelectric transducer; FC, frequency counter; HV, high-voltage. ECDL#1 and ECDL#2 are in different optical tables.

ECDLs. By modulating the injection current of laser diode, the laser frequency was modulated to retrieve the first derivativelike spectrum for laser stabilization. Frequency stabilization of ECDL was realized by feedback controlling the aforementioned PZT and the acoustic-optical modulator (AOM1) with the servo loops of different transfer function. After 80 dB optical isolation, about 7 mW laser power was picked off for sending to potential users, while the rest of the laser power was injected into a tapered amplifier (TA, Sacher TA-0850) to boost the output power to 450 mW. Part of the TA output power was sent to CTSDL #2 system via optical fiber for the beat-note measurements. The rest of the laser power was directed into a cesium cell system for observing the Doppler-free $6S \rightarrow 8S$ hyperfine transitions.

As shown in Fig. 1, a spatial filter including a 20 μm pinhole was installed for presenting a well-defined wavefront curvature in the cesium cell, and a set of neutral density filters (ND in Fig. 1) was applied to control the laser power in front of the cesium cell. For increasing the spectral S/N, two lenses were placed symmetric to the cesium cell with 300 mm focal length, which resulted in a 0.15 mm waist at the center of cell. Two quarter-wave plates were employed for presenting circular polarization of light. We wrapped a current-controlled heating tape onto a 2 cm long cesium cell to control the cell temperature to be always higher than the cold-finger temperature. The diameter of the cesium cell is around 2.54 cm. The heating tape and cesium cell were housed together, and 4 h temperature monitoring showed that the wall temperature variation was below 0.007°C. During the pressure-shift measurements, the wall temperature of CTSDL #1 was fixed at 95°C and 115°C for the different cold-finger temperature regimes. The cold-finger temperature was precisely controlled and adjusted by a TE cooler with 0.05°C temperature accuracy. The other cesium spectrometer (CTSDL#2), which was set up at a different optical table, had a similar experimental setup, except that no taper amplifier, no spatial filter, and no linear polarization of light were used. All the studies of the systematic errors were performed by CTSDL#1, while CTSDL#2 played the role as a stable reference. Blue fluorescence from the transition of $7P$ to $6S$ was detected as a signature of the 822.5 nm TPTs, and the simplified level diagram is depicted in Fig. 1. When in the routine frequency locking, especially in Allan deviation measurements, ND filters in CTSDL#1 were adjusted so that light intensity was the same as what was in CTSDL#2, namely around 770 mW/mm^2 power density in the cell center, while the cold-finger temperatures were all kept at 70°C and the lasers were all frequency modulated with 2 MHz demodulation width, 35 kHz modulation frequency.

Figure 2(a) shows the Allan deviation of two similar CTSDLs, revealing instability less than 300 Hz for sampling time longer than 10 s (4.4×10^{-13} at 60 s sampling time). For investigating the resettability, we recorded the beat note of two similar frequency-stabilized diode lasers for 20 days. Lasers and the

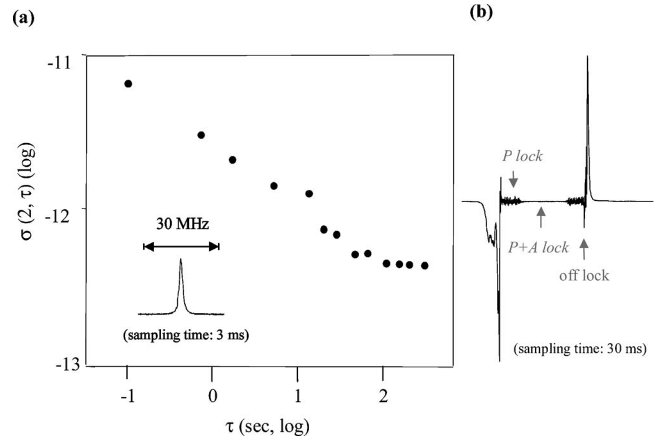

Fig. 2. (a) Two sample Allan deviation $\sigma(2,\tau)$ of the beat frequency between two similar CTSDLs. Both horizontal and vertical axes are on a log scale. Inset, absorption signal retrieved from a lock-in amplifier with 1 kHz chopping frequency. (b) The retrieved first derivativelike signal that revealed S/N of 1500 (30 ms) and the frequency stabilizing process using both PZT (P) and AOM (A) (see text).

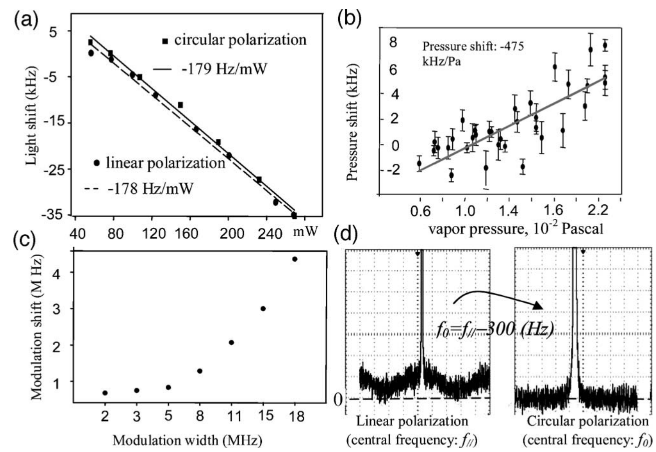

Fig. 3. Studies on the possible laser frequency shifts. (a) Light shift for beam radius of 0.15 mm. (b) Pressure shift for the cold-finger temperature ranging from 68°C to 85°C (see text). (c) Modulation shift. (d) Frequency shift between two different polarizations of light. Dashed line, zero input level. Note that, for linear polarization, the height of pedestal to the whole signal was around 1 to 450.

corresponding electronics were all turned off after each measurement. We found 1.4 kHz resettability that was probably due to the 2°C room-temperature fluctuation during the data acquisition period. Figure 2(b) illustrates our approach on stabilizing laser frequency. Similar S/N (S/N 1500, 30 ms) of the other $6S \rightarrow 8S$, $f=4 \rightarrow f=4$ hyperfine transition could be achieved as well.

For further investigation of the possible systematic errors in frequency locking, we changed the locking conditions of CTSDL #1, while keeping the conditions of CTSDL #2 fixed. As shown in Fig. 3(a) a 179 ± 2 Hz/mW light shift under 0.15 mm beam waist[6] [18.9 ± 0.5 Hz/(mW/mm^2)] was observed by varying the laser power in front of the cesium cell from 15 to 130 mW, or 30 to 260 mW for double pass. Figure 3(b) illustrates that the cold-finger temperature caused a beat-note shift. Note that positive slope corresponds to the redshift of CTSDL#1. When the cold-finger temperature was lower than 84°C, the tendency of pressure shift was essentially similar to what was discovered in Ref. 4. We also tried to change the wall temperature while keeping the cold-finger temperature fixed, and a −90 Hz/°C (−110 kHz/Pa) frequency shift was observed when the wall temperature varied from 70°C to 84°C. The slope was changed when the cold-finger temperature was higher than 84°C; the reasons for this change need to be further investigated. Nevertheless, as was shown in Fig. 3(b), there is little slope regime as the cold-finger temperature lies between 68°C and 84°C. The slope, namely −386±52 Hz/°C or −475 kHz/Pa pressure shift, offers around 20 Hz frequency accuracy when the accuracy of the cold-finger temperature was controlled to be smaller than 0.05°C, which is good for the issue of being a reliable frequency reference. Figure 3(c) shows the modulation shift. When the modulation width became smaller than 5 MHz, 500±50 Hz per MHz modulation width was observed. However, as the modulation width became larger than twice of the spectral width, serious frequency shift happened because nonlinear modulation caused higher harmonics that would induce additional asymmetry of an archived signal. Nevertheless, because a modulation width of 2±0.1 MHz was used in this Letter, a corresponding frequency accuracy of less than 50 Hz could be expected. The other possible cause for frequency-locking error is related to the purity of circular light polarization, especially for the $S-S$ TPTs. A 300 Hz locking-frequency shift was discovered when the polarization of light was adjusted from circular polarization to linear polarization. This effect implies that, for linear polarization of light, the residual first-order Doppler background cannot be ignored. As presented in Fig. 3(d), the height of the spectral pedestal was around 0.2% of the whole signal for linear light polarization, while no pedestal was found for circular light polarization.

Table 1 summarizes all the systematic errors we investigated in this Letter that show promise for employing the CTSDL as a reliable frequency reference. There is space to improve the instability of CTSDL to be below 10^{-13} since our laboratory is not renovated for the metrological purposes. Compared with general national standard laboratories, our laboratory does not have good temperature regulation nor noise isolation from neighboring laboratories. That partially explains the plateau of Allan deviation in Fig. 2 as the sampling time was larger than 100 s. Note that the Allan deviation shown in this Letter is limited by the stability of CTSDL#2. By adjusting the ND filters of CTSDL#1 in Fig. 2, the interaction light power could be raised to more than 200 mW so that one order better of spectral S/N could be achieved. In other words, by comparing the S/N with the aforementioned works in this Letter, frequency instability of below 5×10^{-14} could be expected. However, stability is not the only issue for promoting CTSDL as the candidate of secondary frequency standard. Performing high-precision measurements on the absolute frequency and intercomparisons are also essential procedures that are similar to the development of the 778 nm rubidium standard.[7–11]

Table 1. Properties of our CTSDL

Allan deviation[a]	4.4×10^{-13}
Resettability[b]	1400 Hz
Light shift[c]	−18.9 Hz/(mW/mm^2)
Modulation shift[d]	500 Hz/MHz
Pressure shift[e]	−475 kHz/Pa

[a]For 60 s sampling time.
[b]During 20 day's measurements.
[c]Under 70°C cold-finger temperature.
[d]For modulation width <5 MHz.
[e]Slope averaging from 68°C to 84°C, namely −386 Hz/°C.

The direct application of a cesium TPT-stabilized diode laser is that, in our laboratory, a 25 fs optical frequency comb laser based on 822.5 nm CTSDL is currently built up with 3 kHz carrier-envelope frequency instability. The detailed experimental arrangements and results will be presented elsewhere.

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