Compact extended cavity diode laser system for small optically pumped cesium beam frequency standards

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A compact extended cavity diode laser (ECDL) system operating at 852 nm for small optically pumped cesium (Cs) beam frequency standards was reported. ECDL and a saturated absorption spectroscopy setup were all built in an aluminum box with dimension of 10 × 10 × 7 (cm). ECDL was based on a Littman-Metcaff configuration, whose free-running linewidth was less than 600 kHz. A digital automatic frequency lock unit (AFLU) was developed to lock the laser frequency to specify Cs absorption lines automatically and re-lock it in case of lock broken. With AFLU, the laser frequency was continuously locked for several weeks.

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In the past decades, many laboratory efforts were made in the development of small optically pumped cesium (Cs) frequency standards[1−6]. One of the main challenges to construct a compact and portable optically pumped Cs clock is to develop a compact, low noise, narrow linewidth, and long lifetime laser system whose frequency keeps being locked on a certain Cs atomic transition line stably for a reasonably long time. Besides, as a part of equipment, the laser system should be able to work hands off.

Our laboratory has developed several versions of compact laser systems for compact optically pumped Cs beam clocks[7], and they worked very well[1]. The laser diodes (LDs) used in these laser systems were distributed Bragg reflection (DBR) type. As a result, the linewidth of these laser systems, about tens of megahertz, is not narrow enough for optically pumped Cs clock with right angle incidence of probing laser beam[8]. What is more, as far as we know, no commercial DBR LDs at 852 nm with linewidth below 1 MHz are available so far. Therefore, we use extended cavity diode lasers (ECDLs), with compact volume and narrow linewidth, to take the place of DBR LDs. Many groups have developed their compact ECDLs[9−16], many of which were designed based on Littrow configuration. Though the Littrow configuration is relatively simple, the direction of laser beam changes or shifts as the grating rotates for tuning the laser wavelength[12], which will bring troubles in experiments.

In this letter, we report a compact ECDL system for small optically pumped Cs clocks, whose mechanical design based on the Littman-Metcaff configuration is simple: only the length of the extended cavity can be adjusted by piezoelectric transducer (PZT) when the laser operates. To lock laser frequency, a Doppler-free saturated absorption (SA) spectroscopy setup[9] was built in the same aluminum box with ECDL. Additionally, in order to realize long-term locking and hands off working, we developed a digital automatic frequency lock unit (AFLU) to control the laser operating parameters (temperature, current, and piezovoltage). AFLU is an improved simpler version of the automatic laser frequency lock device in Ref. [7]. Though other group also developed automatic laser frequency lock system[7], our work is simple than them.

Figure 1 shows the schematic of the laser head, consisting of an ECDL (lower part) and a reference spectroscopy setup (upper part). The LD is an AlGaAs diode (JDS Uniphase SDL 5412-H1) without additional antireflection (AR) coating. The diffraction grating, a 1200-line/mm holographic grating, was fixed on a grating mount. The incident angle of the laser beam on the grating was about 80°, and the laser polarization direction was perpendicular to the grooves. The first-order diffraction beam of the grating was reflected by a mirror fixed on a PZT tube which was mounted on a mirror mount (ThorLabs KS05). The laser diode mount, the grating mount and the mirror mount were all fixed on a base plate, which was temperature stabilized by a

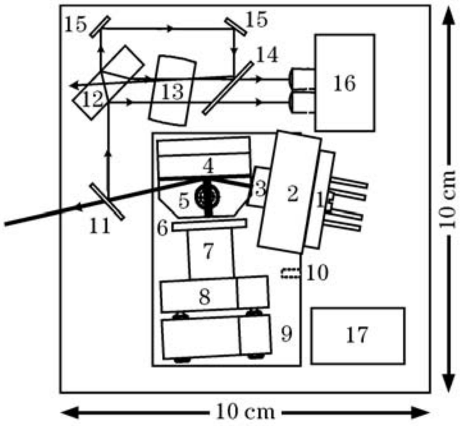

Fig. 1. Schematic of the laser head. 1: Laser diode, 2: laser diode and collimating lens mounting block, 3: collimating lens, 4: diffraction grating, 5: grating mount, 6: mirror, 7: PZT, 8: mirror mount, 9: ECDL base plate, 10: thermistor, 11: beam splitter, 12: thick glass, 13: Cs gas cell, 14: 1:1 beam splitter, 15: mirror, 16: subtraction photodiodes detector, 17: laser diode protection circuit.

thermoelectric cooler (TEC). The length of the extended cavity was about 30 mm and the volume of ECDL was about 100 cm^3.

The zero-order of the grating transmitting through a 4% beam splitter provided the laser output. The reflection beam from the splitter was directed to the Doppler-free SA spectroscopy setup[9]. The volume of the laser head box, including ECDL and the absorption spectroscopy setup, was $10 \times 10 \times 7$ (cm).

When ECDL is aligned carefully, the frequency of the laser can be tuned coarsely to 852.3 nm (vacuum wavelength) by tweaking the screws of the mirror mount to change the grating angle. When the laser frequency is tuned to be close to Cs D_2 lines, the length of the extended cavity is scanned by changing the voltage on the PZT tube, the temperature of the laser diode is simultaneously adjusted to fine tune the laser frequency, and SA curves can be observed, as shown in Fig. 2.

Figure 3 shows the block diagram of the electronic circuits, all of which were homemade. ECDL has output power of 9 mW at 60-mA current. Because the whole curve of $F = 4$ Cs D_2 line was observed (Fig. 2), the successive tuning range of ECDL frequency was more than 0.5 GHz when tuning PZT only. The linewidth of ECDL was evaluated by measuring the spectrum of the beat note signal between two identical free-running ECDLs. As shown in Fig. 4, 3-dB linewidth of the beat note signal was about 800 kHz at a sweep time of one second. Therefore, the linewidth of each ECDL was less than 600 kHz.

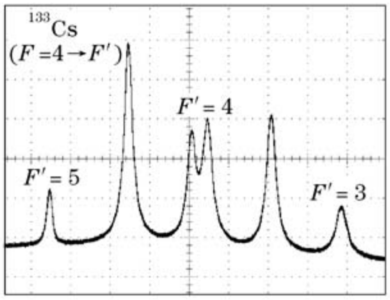

Fig. 2. Saturated absorption curve for ^{133}Cs.

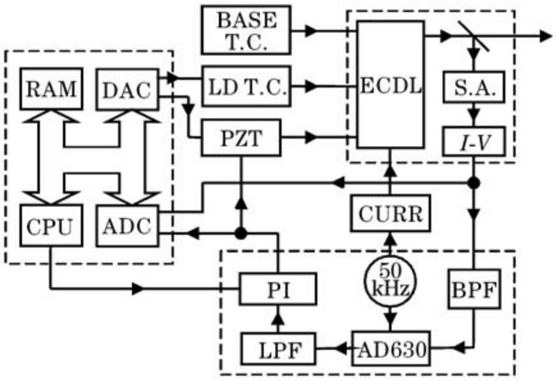

Fig. 3. Block diagram of electronic circuits. S.A.: saturated absorption spectroscopy setup, I-V: current to voltage converter, CURR: negative current source, BPF: band pass filter, LPF: low pass filter, PI: proportion and integration servo circuit, PZT: PZT driver, LD T.C.: temperature controller for the laser diode, BASE T.C.: temperature controller for the base plate of ECDL, RAM: random access memory, DAC: digital-to-analog converter, ADC: analog-to-digital converter, CPU: microprocessor.

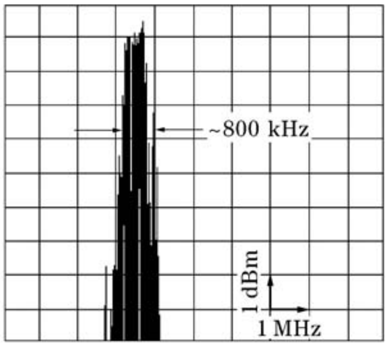

Fig. 4. Spectrum of the beat note signal between two identical ECDLs. Resolution bandwidth (RBW) and video bandwidth (VBW) are 100 kHz; sweep time is 1 s; span is 10 MHz. 3-dB linewidth of the beat note signal is about 800 kHz.

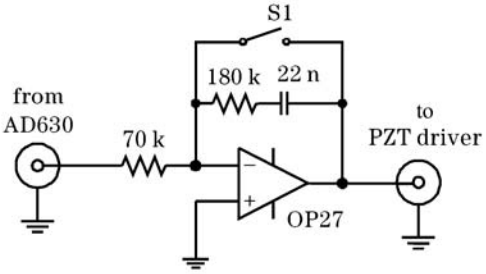

Fig. 5. Proportion and integration servo circuit.

The lower part in Fig. 3 is a servo loop system. The laser frequency was modulated at a rate of 50 kHz by adding a sinusoidal signal to the laser current. The signal from the SA spectroscopy was filtered, and then demodulated by a synchronous demodulator (AD630). The error signal, the filtered output of AD630, was fed to a proportion and integration (PI) servo circuit as shown in Fig. 5. When the switch S1 was close, the integration was reset and the laser was in the status of free running. When S1 was open, the output of PI was fed back to PZT driver to stabilize the laser frequency. In our experiment, the switch S1 was controlled by a logic signal from AFLU. With the servo loop, two identical ECDLs were locked to two different Cs absorption lines and the beat note signal was counted by a counter. The measured frequency drift of the beat note signal was less than 0.5 MHz/day.

The left part in Fig. 3 is AFLU including a microprocessor (ATMEL AT89C52), an 8-bit analog-to-digital converter (ADC) with eight channels, an octal 13-bit digital-to-analog converter (DAC) and a random access memory (RAM) of 8 kB. The outputs of SA setup and PI are sampled by ADC. One output of DAC was directed to PZT driver and another was to control the temperature of LD. One logic signal from the microprocessor was used to control the switch S1 in the PI circuit.

In order to realize automatic locking of laser frequency to the D_2 lines, a program was developed using Keil C51 language and stored in the flash memory of AT89C52. With AFLU, the operating parameters of ECDL were adjusted automatically until the laser frequency was locked.

The process of the automatic locking includes five steps. Firstly, when the system power is turned on, AFLU waits for one minute so that the current source and the temperature controllers can stabilize to the preset values.

Secondly, the temperature of LD begins to be coarsely swept down step by step. The temperature step is about 5 mK, and each step lasts 3 s. Because the temperature of LD is preset higher than the operating value, the laser frequency approaches to the operating value step by step as the temperature is swept. At the same time, another DAC output generates a ramp signal at a rate of about 10 Hz, and the signal is directed to PZT driver. The output of SA setup is sampled simultaneously at a rate of 512 points per period of the ramp signal as piezovoltage scans and the data are stored in RAM. For SA signal is much larger than intensity fluctuations (see Fig. 2), it is easy to distinguish SA signal. Although the mode hops of laser will cause power jumps, the effect of these power jumps is suppressed by the Doppler-free SA setup. When SA signal is detected, the program goes to the next step.

Thirdly, the coarse sweeping of temperature stops and fine adjusting begins. In this step, the temperature step is reduced to about 0.5 mK, the scan range of the piezovoltage is reduced too, and the piezovoltage offset is adjusted to make the scan focus on the detected peak. At the end of each piezovoltage scan, the program checks the sampled data and judges whether the detected peak is the right SA curve. If yes, go to next step; if not, keep changing the temperature of LD.

Fourthly, the program stops fine temperature adjusting and tries to lock the laser frequency. Because the highest peak in SA curve corresponds to the crossover line of $F = 4 \rightarrow F' = 4,5$ (see Fig. 2), it is easy to find the piezovoltage values corresponding to other lines. After the piezovoltage is set to the right value, program opens the switch S1 in PI circuit to close the servo loop. Then SA signal and the output of PI circuit are monitored to judge whether the laser frequency is locked correctly. If these two signals are not in the proper range, the program will close the switch S1 to reset the PI circuit and make the program go back to the second step. Otherwise, the process goes to the final step.

In the final step, the program periodically checks SA signal and the output of PI circuit to prevent them drifting out of the range by slightly adjusting the piezovoltage and the temperature of LD. Virtually, the principle of this practice is to add an integrator, but it is digital. If SA signal goes out of the range or the integrator of the PI circuit is saturated for several seconds, the program will close the switch S1 to open the servo loop and go to the second step. Generally, the laser frequency can be re-locked in one minute.

With AFLU, the laser system can keep continuous locking for several weeks under ordinary laboratory condition. Figure 6 shows a lock performance of experimental data sampled per minute for 12 days. In order to prevent the integrator of PI circuit from saturating, the output of PI circuit was limited in a range of about ±1 V by compensating the piezovlotage offset via DAC output.

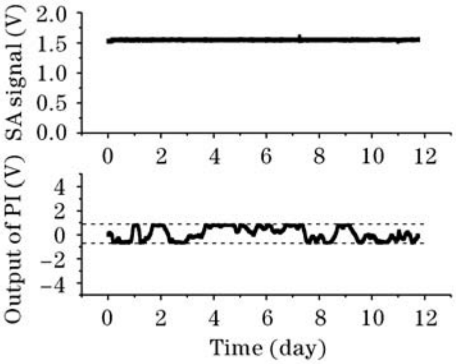

Fig. 6. Lock performance for a long period. The upper curve is SA signal, the lower one is the output of PI circuit, and the short dash lines indicate the limit preset in the program.

Although the laser system can work properly for a long time, there are some challenges need to be overcome so that this system would work hands off for several years. We believe that to use LDs with AR coating would improve the stability, and more careful mechanical design would make the laser system more reliable and more insensitive to acoustic disturbance.

In summary, a compact ECDL system was developed for compact optically pumped Cs beam frequency standards. The free-running linewidth of ECDL was less than 600 kHz, and the successive frequency tuning range is more than 0.5 GHz. With AFLU, the frequency can be automatically locked to a given Cs absorption line preset in the program without any manual intervention after the power turned on, and keep being locked for several weeks. The laser system can re-lock itself in one minute when the frequency lock is broken accidentally. These features make the laser system suitable as a prototype of pumping laser source and probing laser source in small optically pumped Cs beam frequency standards. The laser system and the automatic locking technique can also be used in other possible applications, for instance, in a laser-pumped rubidium atomic clock or as a compact, portable wavelength reference.

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