The application of sample-and-hold circuits in the laser frequency-shifting

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A new method of frequency-shifting for a diode laser is realized. Using a sample-and-hold circuit, the error signal can be held by the circuit during frequency shifting. It can avoid the restraint of locking or even lock-losing caused by the servo circuit when we input a step-up voltage into piezoelectric transition (PZT) to achieve laser frequency-shifting.

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Lasers with stable frequencies are essential in many fields of research[1−4] such as in laser cooling and trapping atoms[5] and Bose-Einstein condensation experiments[6,7]. It is required that the line width of lasers is less than 1 MHz and does not have long-term drift. Yet on some occasions, it is often necessary to rapidly shift the frequencies of cooling beams from the detuning $-2\Gamma - 3\Gamma$ to $-6\Gamma - 8\Gamma$ (Γ is the natural width of the atom) to lower the temperature[8,9]. Normally, we have two means to achieve the quick frequency-shifting. One way is to lock the laser frequency and let the output beam double pass an acousto-optical modulator (AOM) so that we can shift the laser frequency by changing the modulation frequency of AOM. The advantage of this method lies in its precision. So it is often used in such experiments that are highly sensitive to laser frequency as in the atomic fountain clocks[10]. However, it also bears some disadvantages. Double pass causes a great deal of output power loss by as high as 30 percent or even higher under some circumstances. Meanwhile, the laser beam's spatial profile will downgrade. Besides, with the diffraction efficiency of the AOM being in correlation with modulation frequency, frequency-shifting will naturally cause change in the power of output beam. The other way is to change the error signal and force laser frequency into shifting through the adoption of a feedback loop. Some researchers make current pass through a solenoid to produce a magnetic field. When they changed current, the saturated absorption signal was moved and the laser frequency was tuned[4,11]. This method fits to peak-locking. Since peak-locking needs to modulate the light or the magnetic field, the speed of frequency-shifting is limited by the modulation frequency and the time constant of the phase-sensitive detection. Apart from the two common ways hereinbefore, we may also achieve the frequency-shifting by means of directly controlling the piezoelectric transition (PZT). The problem of this method is, however, when the laser frequency is locked, frequency-shifting will be affected by the feedback circuit, which restrains frequency-shifting or makes it worse, induces frequency out of locking. Although we can decrease the bandwidth of the servo system to make it not sensitive to sudden frequency change, it will, nevertheless, also downgrade the frequency stability at the same time. For instance, if the shifting-and-holding time in new point is 20 ms, the bandwidth of feedback circuit must be reduced to below 50 Hz at least. In this case, the circuit only plays a role in restraining the low frequency mechanical vibration, but exerts no effect on higher frequency noise at all. In this paper we will introduce a new, simple, and low-cost method for quick frequency-shifting. The method is based on the following: when we do some laser cooling experiments, for example, loading cooled atoms into a magnetic trap, there is no such a high demand for the precision of frequency-shifting. Since the cooling effect in detuning -6Γ and -8Γ is not so distinctively varying, and the rest part of the experiment will not be affected, we might consider shifting laser frequency directly. To avoid the forenamed problem, we use a sample-and-hold circuit to hold the error signal during the whole period of frequency-shifting (ranging from a couple of dozens of milliseconds). The step-up voltage is added to the output voltage of a servo controller. Then it is sent to PZT for frequency-shifting.

The experimental setup is shown in Fig. 1. The laser source is provided by a grating-feedback external-cavity diode laser (NewFocus 6000) with a wavelength of 780 nm. After passing through an optical isolator, the laser beam is divided by a beam splitter. A part of it is used in

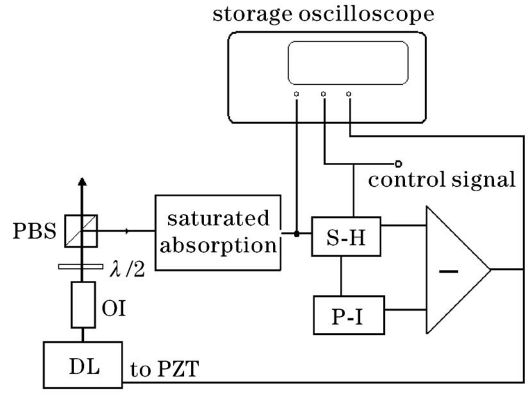

Fig. 1. Schematic diagram of the experiment setup. DL: diode laser; OI: optical isolator; $\lambda/2$: half-wave plate; PBS: polarization beam splitter; S-H: sample-and-hold circuit; P-I: proportion-and-integral circuit.

a saturated absorption spectrometer. In order to monitor frequency-shifting, we select one side of a well-resolved saturated absorption peak as the error signal. In this experiment, we lock its frequency in blue detuning of C_3 peak of ^{87}Rb D2 line (C_3 peak is in the middle of $5S_{1/2}$ $F=2 \rightarrow 5P_{3/2}$ $F'=2$ and $5S_{1/2}$ $F=2 \rightarrow 5P_{3/2}$ F'=3 transition of ^{87}Rb). The locking range is from peak to valley, about 50 MHz in this case. The error signal is first sent into a sample-and-hold circuit, and then input to a P-I (proportion-and-integral circuit) servo controller. The bandwidth of the P-I servo controller is about 1 kHz. The voltage for frequency-shifting is provided by the computer signal which is also responsible for sampling and holding controls. In our experiment, we shift laser frequency about 30 MHz. The output voltage from a P-I servo controller and the frequency-shifting voltage are synthesized by a subtraction circuit before it is sent to the PZT of the laser to control the frequency. The saturated absorption signal, the computer controlling signal, and the voltage input to PZT are all recorded by a storage oscilloscope. Figure 2 is the sample-and-hold circuit. LF398 sample-and-hold integrated circuit (IC) is used in our experiment, which is a low cost general purpose sample-and-hold circuit. Pin 7 and pin 8 are two controlling ports of this IC. When the controlling voltage between pin 7 and pin 8 is higher than 1.4 V, LF398 is in sampling state, and the output signal follows the change of the input signal. When the controlling voltage steps down and the potential difference is smaller than 1.4 V, the circuit changes into holding state while the output voltage maintains the same level as the input signal just before controlling voltage steps down. By setting a 0.01 μF holding capacitor value, the declining rate of holding voltage is kept under the control of less than 10 mV/s, which satisfies the requirement of our experiment. To avoid the high frequency noise produced by computer or transmission, we use an optocoupler (4N35) to filter it. When the controlling signal from the computer is at low level (0 V), the optocoupler does not conduct. The potential difference between pin 7 and pin 8 is about 5 V. So the sample-and-hold circuit is in sampling state. If the computer signal jumps up to high level (5 V), the optocoupler conducts and the potential difference between pin 7 and pin 8 is smaller than 1.4 V. The sample-and-hold circuit's output is equal to the error signal just before the computer signal jumping up. At the same time, the dividing-voltage from adjustable resistor is used for shifting frequency.

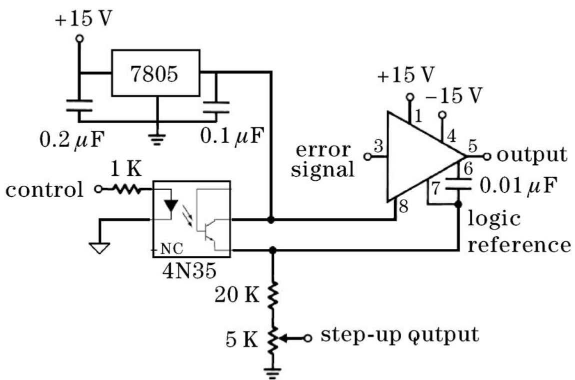

Fig. 2. Sample-and-hold circuit.

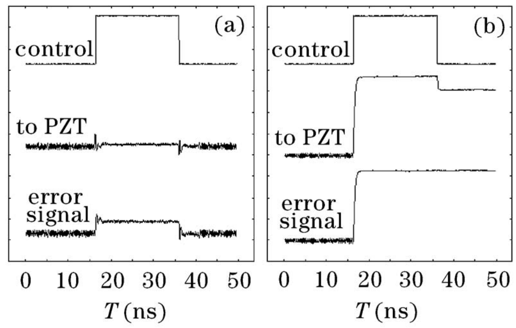

Fig. 3. Experimental results when error signal is directly sent into the servo circuit without passing the sample-and-hold circuit: (a) the frequency-shifting is restrained, (b) lose lock.

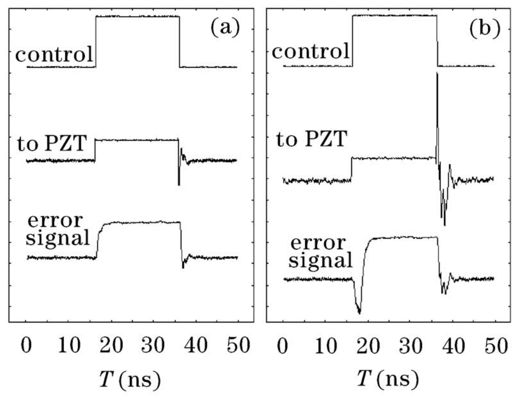

Fig. 4. Experimental results when the sample-and-hold circuit is applied. The frequency-shifting is about 30 MHz.

If the error signal is directly sent into the servo circuit without passing the sample-and-hold circuit, either of the following two phenomena will be observed when we try to input the voltage to shift the frequency. One is that the servo circuit still somewhat plays a role. In other words, when the step-up voltage is input, the servo circuit will restrain the frequency-shifting, as shown in Fig. 3(a). Or, when momentary laser frequency goes beyond the locking range, the diode laser will lose locking. In this case, the laser frequency will not change back to the initial value after the step-up voltage disappears, as shown in Fig. 3(b). And yet, if we adopt the sample-and-hold circuit, both of the two above-mentioned cases can virtually be avoided. This means that we can shift the laser frequency without encountering any technical hitch, as shown in Fig. 4. As is demonstrated in Fig. 4(b), even when the laser frequency has actually exceeded the locking range, it can still be relocked after frequency-shifting ends. The response time of PZT is about 3 ms if the frequency-shifting is more than 30 MHz. After controlling voltage jumps back to the original level, there is a short-term oscillation. And after that, the frequency returns to the initial value.

Besides NewFocus 6000, another diode laser (Topic DL100) is also employed to do the same experiment and the result turns out to be quite living up to our expectation. Using DL100 as the seed, we amplify the laser beam through a tapered amplifier diode laser system (TA100). Then it is used to cool and trap atoms. Under a typical experimental condition, we can load about more than

1×10^8 ^{87}Rb atoms into a quadrupole trap, which indisputably proves the effectiveness of our method.

Using this circuit, we can also avoid some severe disturbance, which often induces the laser frequency out of locking. In magnetic atom trapping experiments, for example, we need to use some mechanical shutters to cut cooling beams and repumper beams thoroughly. However, shake produced by the closing of shutters often causes the laser frequency to lose lock. Yet, if we hold the error signal the moment before shutters close and let it change back to sampling state again after shake vanishes, the problem of lock losing of laser frequency can be effectively avoided.

The simple-and-hold for frequency-shifting also can be achieved by a computer with an A/D -D/A card[12]. But the circuit introduced in this paper is simpler and lower in cost.

To sum up, by applying a sample-and-hold circuit in the process of laser frequency-shifting, the error signal can be held by the circuit during frequency-shifting. Thus, the servo circuit will not disturb the shifting and not induce the frequency out of locking. In other words, it is not only cost-efficient, but a highly reliable method for frequency-shifting experiment due to its capability to avoid severe disturbance which may end up causing frequency to lose lock.

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