Robust external cavity diode laser system with high frequency stability for Cs atomic clock

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A robust external cavity diode laser (ECDL) insensitive to mechanical vibration is built with an interference filter for selecting wavelength and a cat-eye reflector for light feedback. The free-running laser has a linewidth of 72 kHz. The laser frequency stability reaches 3×10^{-12} at 1-s integration time in terms of relative Allan variance based on the saturation absorption spectrum.

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External cavity diode laser (ECDL) with high spectral purity has many applications in many fields, such as atomic physics, atomic clock, and coherent light communication[1−6]. In atomic clocks, ECDLs are used to cool the atoms down to several microkelvin and detect the atomic population, which generates an error signal to stabilize the output frequency of atomic clocks. The quality of the laser directly impacts on the performance of atomic clock. Especially, the linewidth and frequency stability should be first considered[7−9].

In the most common ECDLs of the Littman or Littrow configuration[1], laser linewidth can be narrowed to a few hundred kilohertz. However, such a design is sensitive to the optical misalignment induced by mechanical vibration[10]. This restricts the application of ECDLs under some special conditions, for example in space or commercial optically pumped Cs clock. Although a distribution feedback (DFB) laser or a distributed bragg reflector (DBR) laser with high mechanical stability has been developed for application in atomic clock, a typical linewidth of several megahertz[11] may limit the further improvement of atomic clock.

In this letter, we present an ECDL with narrow linewidth and high mechanical stability. Moreover, to stabilize the laser frequency, a two-stage reliable servo loop is developed based on the saturation absorption spectrum. In our construction, an interference filter (IF), which consists of multiple thin layers of dielectric material, is used to select the wavelength, and a cat-eye reflector serves as the feedback mirror. This design firstly proposed by Zorabedian *et al.*[12] has been chosen for space lasers in the PHARAO project[13].

The construction of the ECDL is shown in Fig. 1. The light emitted from laser diode (LD) is collimated by an aspheric lens (CL1) with large numerical aperture(NA). A lens (L1) focuses the collimated light on the partial reflector (R) which forms a cat-eye reflector. This reflector reflects partial light back to LD so that an external cavity is formed. The external cavity length is about 10 cm, which is adjusted by a piezoelectric transducer (PZT) attached on the reflector. The cat-eye reflector with reflectivity of 30% keeps the external cavity valid even if the optical components inside cavity are slightly misaligned. The focused light is collimated by the second aspheric lens (CL2). An IF is placed between the CL1 and the L1. The IF consisting of multiple thin layers of dielectric material with super-narrow passband of 0.3 nm and high transmission of 90% serves as laser wavelength selection. The wavelength of the transmitted light is changed by adjusting the filter′s angle. Compared with the Littrow or Littman cofiguration, the IF and the cat-eye reflector replace the grating to select laser wavelength and form an external cavity. We can easily adjust laser frequency and optimize optical feedback. Furthermore, because the IF and the cat-eye reflector are insensitive to the incident angle[13], this design has higher mechanical stability than the design of Littrow or Littman cofiguration.

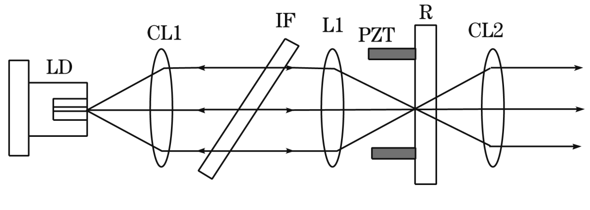

Fig. 1. Schematic of the ECDL structure.

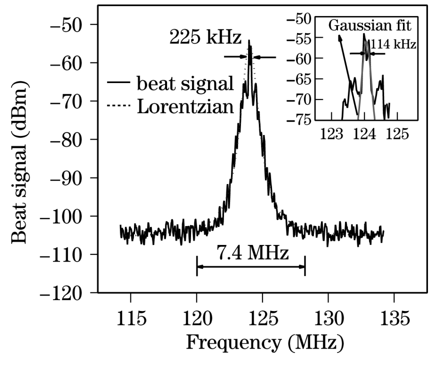

Fig. 2. Spectra of the beat note signal between two identical ECDLs. The spectrum analyzer (Agilent E4405B) has a resolution bandwidth of 1 kHz and sweep time of 2 s. The inset shows the central sharp peak.

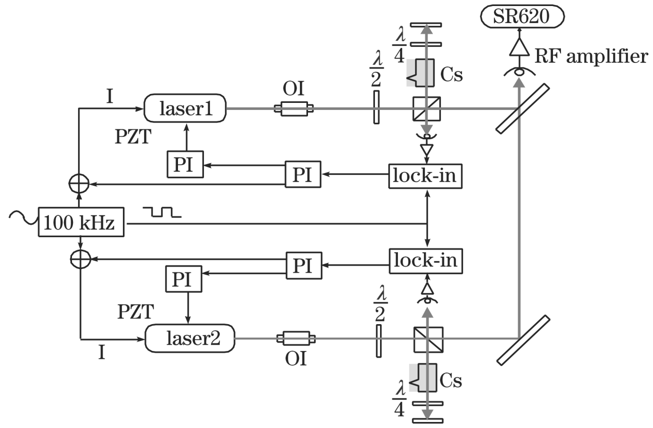

Fig. 3. Schematic diagram of servo loop and frequency stability measurement of the diode laser system. OI: optical isolator; SR620: SR620 time interval and frequency counter; RF: radio frequency.

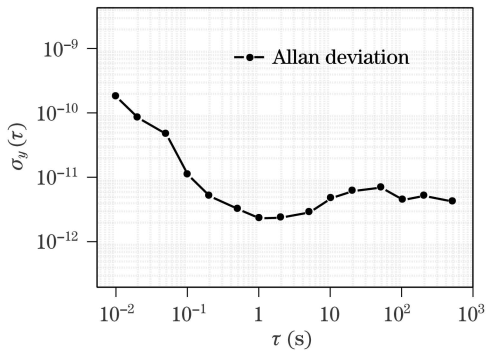

Fig. 4. The diode laser system frequency stability in terms of Allan deviation.

In the experiment, the diode (SDL5422) had an emitted wavelength at 852 nm close to the Cs atom D_2 line with maximal output power of 150 mW. The output facet of the diode was not specially antireflection coated. A thermoelectric cooler (TEC) and a thermistance in the diode package stabilized the LD's temperature below several millikelvin. Owing to the feedback light, the diode threshold current reduced from 16 to 10 mA. The temperature of the external cavity was also stabilized by another TEC below 10 mK. The current source was homemade with a low fluctuation of less than 1 μA.

In order to determine the linewidth of the laser, we measured the beat signal between two free-running identical lasers. The beat signal spectra are shown in Fig. 2. The full power of the beat signal almost concentrates on the frequency domain of 7.4 MHz, which shows that our laser has higher spectral purity than others with the same configuration[13,14]. The wings of the beat signal are fitted by a Lorentzian[2]. The fitting shows that the laser has a −3-dB linewidth of 225 kHz, corresponding to the linewidth of 112.5 kHz for each individual laser. However, the −3-dB linewidth is determined by the sharp peak in the center of profile line. The peak profile line fitted by Gaussian shape[2] gives the linewidth of 72 kHz. This result is much better than the result of grating external cavity laser[15] or DFB/DBR laser[16]. Such narrow linewidth of the ECDL guarantees a high performance of Cs atomic clock. The output laser with higher spectral purity is easily obtained by decreasing laser current noise that broadens the wings of beat signal.

To stabilize laser frequency, a servo system is developed based on the saturated absorption spectrum (see Fig. 3). The laser frequency is modulated by a signal of 100 kHz via the injected current. The saturated absorption signal is demodulated as an error signal through a lock-in amplifier. The error signal through the first proportional-integral (PI) controller is applied to the diode laser current. To avoid the laser mode hopping and increase the long term operation of the servo loop, the second PI controller is used to generate the PZT voltage correction signal.

The whole servo system is realized by using homemade dedicated analog electronics. Under ordinary laboratory condition, the laser system has kept continuous locking for several weeks. Although optical table vibrates induced by rotary vane pump sometimes, the diode laser system is not unlocked, which indicates that our ECDL has the characteristic of anti-vibration.

To evaluate the laser frequency stability, each laser is stabilized on the different peaks of the saturated absorption spectra ($F = 4 \rightarrow F = 5'$ line, crossover between $F = 4 \rightarrow F' = 5$ and $F = 4 \rightarrow F' = 4$) and the frequency difference is measured by a frequency counter. To avoid the modulation broadening, both the laser systems are modulated by the same 100-kHz signal. Both the output beams are superimposed on a fast photodiode. The resulting beat note signal is then amplified and counted by SR620. The measurement result is shown in Fig. 4 in terms of the relative Allan standard deviation versus the integration time. The result shows that the laser has the frequency stability of 3×10^{-12} at 1-s integration time as good as the grating ECDL used in atomic clock[15]. A little degraded frequency stability is found at 10–100 s, This is probably due to the fact that the reference Cs cell is not temperature stabilized. To achieve the higher frequency stability, some improvements about the frequency reference, such as temperature stabilization and magnetic field shield of the Cs cell, should further improve laser frequency stability to 10^{-13} level.

In conclusion, to reduce sensitivity to mechanical vibration of ECDL, a robust ECDL system is built with an interference filter and a cat-eye reflector. The free-running laser has a linewidth of 72 kHz. The high frequency stability of 3×10^{-12} at 1-s integration time is achieved by homemade servo loop and a typical saturated absorption setup.

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