A 657-nm narrow bandwidth interference filter-stabilized diode laser

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We present a 657-nm external cavity diode laser (ECDL) system, where the output frequency is stabilized by a narrow-band high transmission interference filter. This novel diode laser system emits laser with an instantaneous linewidth of 7 kHz and a broadened linewidth of 432 kHz.

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External cavity diode lasers (ECDLs)[1] are widely used in laboratories in such fields as precise measurement, atom manipulation, and telecommunication. Typical designs involve diffraction grating for wavelength selection and stabilization. Another design uses a narrow-band interference filter placed in a linear cavity as the frequency selective element. Although less popular, this configuration shows outstanding performance. Different from the commonly used Littrow and Littmann configurations[2,3] with diffraction grating involving light reflections, its linear cavity design with the filter is less sensitive to misalignment induced by mechanical and thermal disturbances and also reduces the angle change when the laser wavelength is tuned by adjusting the angle of the frequency selective element[4]. With these merits, the interferance filter (IF) configuration was chosen for the PHARAO project[4] for a space-born laser system. In our research on a transportable calcium atomic clock[5,6], a mechanically stable laser at 657 nm was required for the probing of the clock transition.

In this letter, we describe the IF-based laser system design in detail. A 0.45-nm full-width at half-maximum (FWHM) of the interference filter is then presented. In the following, we show the heterodyne beating result exhibiting a 7-kHz instantaneous linewidth and a 432-kHz broadened linewidth.

The main mechanical and optical design of the laser[4,7] is presented in Fig. 1. Light is emitted from an AlGaInP laser diode (LD) (HL6545MG, Opnext, USA) without any anti-reflection coating, whose output power is 130 mW and then collimated by an aspheric lens (352671, LightPath, USA) with a focal length f of 4 mm and a numeric aperture (NA) of 0.6. A "cat's eye"[5] consists of an aspheric lens (352260, Light Path, USA) with f=15.3 mm and a partial reflecting mirror with 60% transmission in front. The partial reflecting mirror is glued onto a piezo-electric transducer (PZT) tube for micro position adjustment. The cavity formed by the mirror and the back facet of the diode is approximately 70 mm in length. After transmitting across the partial reflecting mirror, the output light is then re-collimated by an aspheric lens identical to the one forming the "cat's eye". The interference filter is placed inside the cavity on a mirror mount with fine angle adjustment. By tilting the filter to different angles, the output wavelength can be coarsely tuned.

All optic elements are fixed to a base machined from a whole piece of aluminum for the sake of mechanical stability and temperature control. The whole system is then sealed in a metal box with 3-mm Styrofoam lining the inside surface to insulate it from the outside environment thermally. The temperature control of the system is carried out by a thermoelectric cooler (TEC) placed between the base and the metal box. The TEC controls the temperature of the LD and the external cavity.

The interference filter is formed by layers of dielectric materials having different diffraction indices with different thicknesses deposited on the optical substrate, which as a whole functions as a combination of the Fabry-Pérot interferometers. Incident light undergoes multiple reflections within the layers and passes through the filter only when the wavelength is within the range. We perform a measurement of the filter transmission. The incident laser is provided by another commercial ECDL, and its wavelength is tuned from 656.8 to 658 nm under the monitoring of a wavemeter (WA-2500, Burleigh, USA). According to the result presented in Fig. 2, more than 70% of the transmission can be achieved at a nominal wavelength of 657.4 nm with an FWHM of 0.45 nm. The filters are fabricated with a 0.5-mm-thick substrate with larger dimensions and then cut into small pieces of 5 ×5 (mm).

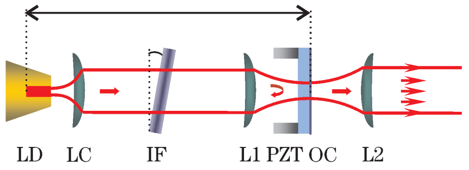

Fig. 1. Schematic of the external cavity laser with an IF for wavelength selection. LC is the collimating lens, OC is the partially reflective out-coupler, L1 is the lens forming a "cat's eye" with OC, and L2 is the lens providing a collimated output beam.

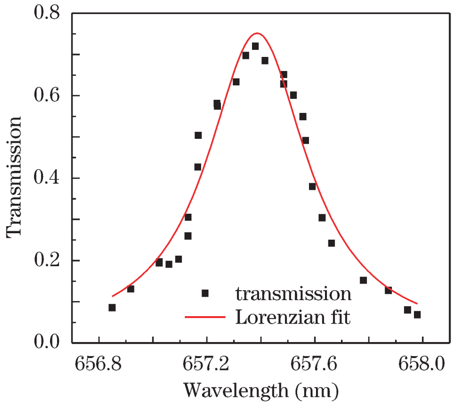

Fig. 2. Filter transmission at an incident angle of 8° as a function of the incident wavelength. The incident laser is provided by another ECDL. The wavelength is measured by a wavemeter (Burleigh WA-2500).

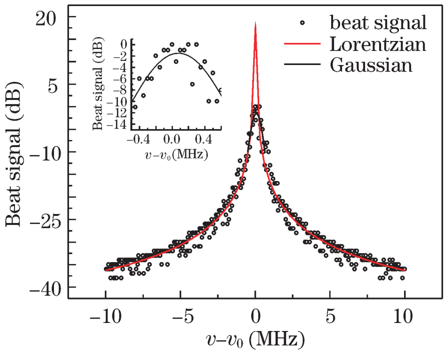

Fig. 3. Power spectra of the beat signal between two identical free-running 657-nm lasers. The resolution bandwidth of the spectrum analyzer is set to 10 kHz, video bandwidth to 1 kHz, and sweep time to 1 s. The FWHM of the Lorentzian is 10 kHz, and the Gaussian fit is 611 kHz.

The angle of the highest transmission of the 657-nm light is designed to be 8° to avoid the light reflected from the filter feeding back into the diode.

To determine the spectral properties of the laser, we carry out a heterodyne beating experiment between two identical, free-running laser systems. Beams from two such lasers are superimposed on a photo detector. The beat signal is then fed into a spectrum analyzer controlled by a polarization controller (PC).

One typical beat signal is shown in Fig. 3, which can be treated as a Lorentzian whose center frequency is distributed randomly. We fit the points in the flanks with the difference of laser frequency v and the center frequency v_0 satistying $|v-v_0|$ >0.5 MHz with a Lorentzian to determine the instantaneous linewidth, which indicates the white noise level, and the central part within +/−0.5 MHz with a Gaussian to determine the broadened linewidth, which indicates the technical frequency noise. The FWHM of the Lorentzian fit and the Gaussian fit is 10 and 611 kHz, respectively. Thus, the instantaneous Lorentzian linewidth is calculated to be 7 kHz, and the broadened Gaussian linewidth is 432 kHz according to the above fits. The two kinds of noise can be treated separately, and the fitted linewidths are valid although the central part of the Lorentzian fit is higher than the data points.

By changing the incident angle of the filter, we can achieve a coarse tuning range of nearly 9 nm with injection current I = 90 mA ($I_{\max}$ = 170 mA). In this range, the single mode operation is obtained, which can be observed with a scanning Fabry-Pérot interferometer with a finesse of 200. Mode hopping can be observed frequently, and the output wavelength jumps accordingly. To tune the wavelength continuously, the mode hopping gap of the wavelength can be bridged by a current tuning combined with PZT adjusting. Based on the direct measurement of the wavelength, the two modes seem to emerge alternately, and the output wavelength hops back and forth while changing nearly continuously as the current is ramped up. The finest wavelength tuning utilizes the PZT. The hopping-free tuning range is about 0.5 GHz.

In conclusion, we build an ECDL using an interference filter for wavelength discrimination, of which the wavelength is 657 nm and the Lorentzian linewidth is 7 kHz. This laser is intended to be implemented in a transportable calcium atomic clock. Research on frequency locking[8−10] will be carried out in the future.

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