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Broad bandwidth interference filter-stabilized external cavity diode laser with narrow linewidth below 100 kHz*

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Interference filter-stabilized external cavity diode lasers (ECDLs) have properties of simple configurations, high stabilities, and narrow linewidths. However, the interference filter used in common ECDL designs requires an ultra-narrow bandwidth (about 0.3 nm) to achieve mode selection, that is considerably expensive and not yet available for a wide range of wavelengths. In this paper, a robust ECDL using an available broad bandwidth (about 4 nm) interference filter as the wavelength discriminator is constructed and tested. The ECDL demonstrated a narrow Lorentzian fitted linewidth of 95 kHz and a spectral purity of 2.9 MHz. The long-term frequency stability of the ECDL reaches 5.59×10^{-12}.

Keywords: external cavity diode laser, narrow linewidth, high frequency stability

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1. Introduction

Narrow linewidths (<1 MHz) are essential in a variety of laser applications, such as atom clocks, atomic physics, precise measurements, and coherent light communication.[1–5] Moreover, lasers with narrow linewidths have great potential in Faraday anomalous dispersion optical filters.[6] In general, narrow linewidths can be effectively achieved by external cavity diode lasers (ECDLs). One common method to construct an ECDL is using a diffraction grating as the optical feedback and wavelength discrimination component in either the Littrow[7] or Littman–Metcalf[8] configurations. However, these designs are sensitive to the ambient pressure and optical misalignment induced by the mechanical and thermal deformation.[9]

An alternative approach is to simultaneously employ a narrowband interference filter, placed in the linear cavity as the wavelength discriminator, and a mirror located at the end of the cavity as the optical feedback component, and has been proved to have a greater alignment tolerance and wider tunability.[6,9–12] Nevertheless, the interference filters used in these designs have an extremely narrow bandwidth (~0.3 nm) comparable to the intrinsic mode spacing of the diode laser that are not readily available at a broad range of wavelengths, resulting in higher cost, restraining the popularization of this method.

In this paper, we use a readily available broad bandwidth (~4 nm) interference filter to achieve single mode operation in an ECDL. The ECDL produced a narrow Lorentzian fitted linewidth of 95 kHz, spectral purity of 2.9 MHz, and long-term frequency stability of 5.59×10^{-12}, exhibiting an excellent performance.

2. Design of the ECDL

The configuration of the ECDL is depicted in Fig. 1. The F–P diode laser with a center wavelength of 852 nm was coupled to a heatsink, and the temperature was precisely controlled by a TEC combined with a thermistor. The front facet of the diode was coated for anti-reflection and the rear facet was coated for high reflection. An aspheric lens with 4.3 mm focal length and 0.55 numerical aperture was located in the front of the output facet to collimate the laser beam. Then an interference filter was placed behind the collimating lens as the wavelength discriminator. At the end of the external cavity, a cat's eye reflector[9] consisting of an aspheric lens with 18.6 mm focal length and a partially reflecting mirror with 30% reflectivity was constructed to provide optical feedback. Such a cat's eye reflector can decrease the sensitivity to the optical misalignment and maximize the feedback efficiency. The overall external cavity length counted from the output facet of the diode laser to the front facet of the partially reflecting mirror was 85 mm.

To manage the output beam of the ECDL conveniently, a re-collimating lens is used to obtain the collimated light. All optical components were placed in a 30 mm cage system (see the lower row in Fig. 1). The position of each lens was finely tuned along the output direction, and the angle of

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the partially reflecting mirror was finely adjusted by a precision mirror mount. When set to the appropriate position, all components were fixed firmly to decrease acoustic resonances. The ECDL was then placed in an enclosed aluminum shell to shield the acoustic vibrations and electromagnetic interference from the environment.

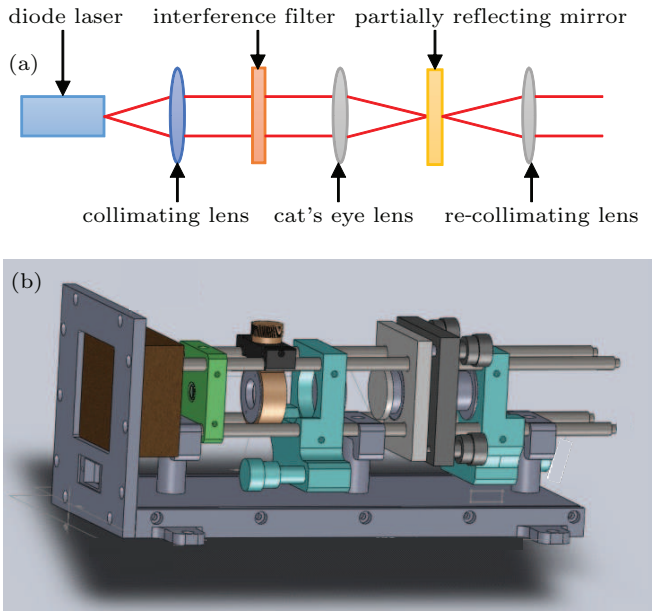


Fig. 1. (color online) (a) Schematic of the ECDL using an interference filter as the wavelength discriminator. (b) The 3-dimensional configuration of the ECDL.

The filter used in the ECDL design was a commercial filter (LL01-852-12.5, Semrock) manufactured by Semrock with a wide bandwidth. Its transmission spectrum is shown in Fig. 2.

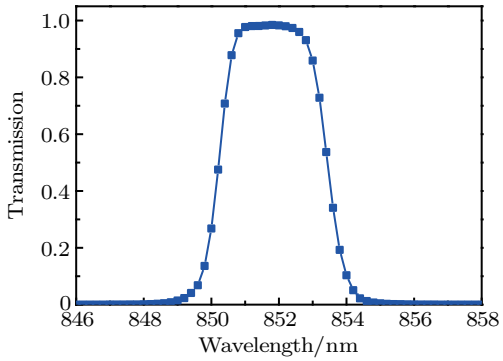


Fig. 2. (color online) The transmission spectrum of the interference filter.

The transmission spectrum was approximately rectangular with a relatively sharp edge. The peak transmission of the filter was as high as 97%, introducing a few optical power losses in the external cavity. The bandwidth of the filter was ~4 nm, ~13 times larger than that of the filters used in similar filter-based ECDLs.[6,9–12]

3. Results and discussion

Figure 3(a) shows the curve of the light output power versus current (*L*–*I*) of the diode laser without an external cavity measured by a power meter at room temperature. Here, the diode laser had a threshold of 40 mA, an output power higher than 50 mW, and a slope efficiency of 0.66 mW/mA. The spectrum of the diode laser measured at 54 mA under a continuous wave condition at 28 °C is also displayed in the inset in Fig. 3(a), which shows a center wavelength of 852.355 nm and a spectral linewidth of 0.31 nm. After adding the external cavity to the diode laser, iterative adjustment of the focus and external cavity alignment were implemented to optimize the optical feedback. Optimum alignment was accomplished when the threshold was reduced to a minimum.[13] As can be seen clearly from Figs. 3(a) and 3(b), the threshold was reduced from 40 to ~ 30 mA (the minimum threshold of the ECDL), indicating that a strong optical feedback was realized and a good alignment was accomplished.[13] However, due to the insert loss introduced by the optical components in the cavity, the slope efficiency and output power decreased to ~ 0.5 mW/mA and 32 mW, respectively.

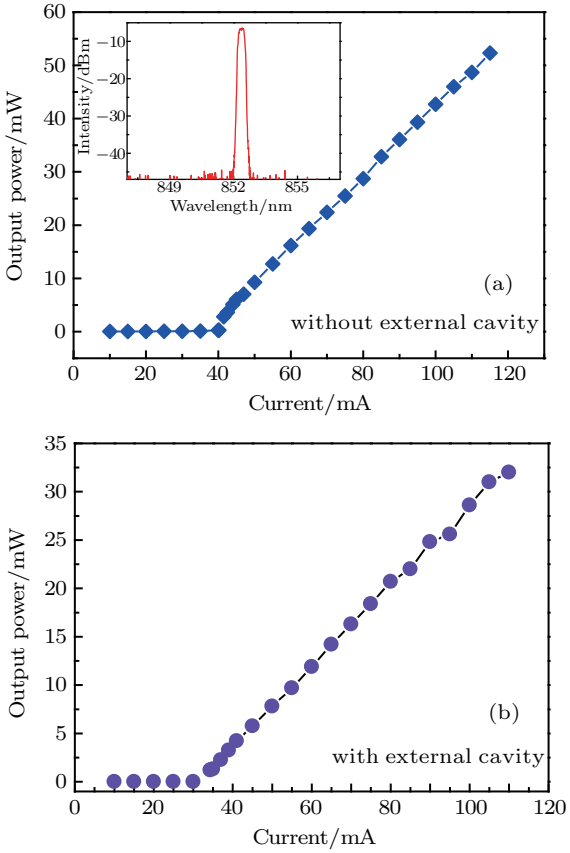


Fig. 3. (color online) (a) Light output power versus current (*L*–*I*) for the diode laser without an external cavity. The spectrum of the diode laser measured at 54 mA under a continuous wave condition at 28 °C is shown in the inset. (b) *L*–*I* curve for the ECDL.

After good alignment was no longer achieved, the linewidth of the ECDL was determined by a delayed self-homodyne linewidth measurement technique,[14] that mixes

the optical wave down to the RF range. Results from the self-homodyne technique measured by an RF spectrum analyzer (Agilent E4440A) are displayed in Fig. 4. The full power of the beat signal was almost concentrated on the frequency domain of 2.9 MHz, showing that the laser had a higher spectral purity than others with similar configurations.[1,6,9,11] The beat note signal was centered at a frequency of 0 Hz. Due to the measurement range of the spectrum analyzer (Agilent E4440A), from 3 to 26.5 GHz, the beat signal near 0 Hz could not be detected or displayed by the analyzer, and therefore led to a deep dip near 0 Hz. However, a Lorentzian line shape function fitted the wings of the beat note very well, with a 190 kHz FWHM, corresponding to a 95 kHz FWHM linewidth of the ECDL.

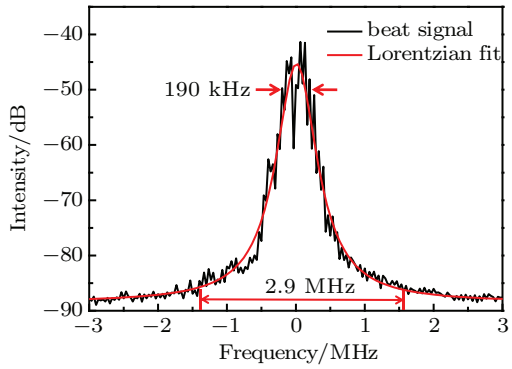


Fig. 4. (color online) Spectrum of the beat note measured by the delayed self-heterodyne measurement with a 2.5 km delay fiber.

Here, we discuss the principle of mode selection of the ECDL. For an ECDL with an interference filter for wavelength selection, the output frequency is determined by the combination of frequency-dependent gain and loss factors: the semiconductor gain profile, the dispersion of light through the interference filter, and the internal and external cavity modes.[15,16] In principle, a few external cavity longitudinal modes can be selected by the diode gain curve. Then the gain for most of these modes is decreased by the sharp edges of the broadband filter, leaving a small number of modes with a similar gain. By rotating the filter, the net gain of those remaining modes within the filter bandwidth varies, leading to just one dominant external cavity mode. By varying the diode mode spacing via the diode injection current, the diode temperature and rotation of the filter, the dominant external cavity mode can be controlled precisely.

The diode laser in our ECDL has a physical cavity length of $L_{\mathrm{D}} = 1$ mm and a refractive index of $n = 3.6$, giving a mode spacing of $\Delta\nu = c/2nL_{\mathrm{D}} = 41.67$ GHz. Since the bandwidth of the filter is 4 nm (1653 GHz), up to 39 diode laser modes could be transmitted through it. Most of these modes are then suppressed by the sharp edge of the transmission function of the filter, leaving a small number with similar gain. By combining the semiconductor gain profile of the diode laser and cat's eye reflector, an inherently good mode matching between the diode laser and external cavity could then be achieved,[15,16] leading to a narrow linewidth.

We then use a servo system[1] based on the saturated absorption spectrum to stabilize the frequency of the ECDL. The setup for obtaining the saturated absorption spectrum is shown in Fig. 5. An optical isolator was set in the output direction to prevent the reflected light coming back to the laser diode. A $\lambda/2$ plate was placed in front of the PBS. By controlling the polarization of the beam, the splitting ratio of the PBS was set. Then a Cs cell and $\lambda/4$ plate were placed between the PBS and PRM. The real-time monitoring of the ECDL wavelength was then conducted via a wavemeter. Finally, a PD combined with an oscilloscope was utilized to observe the saturated absorption spectrum.

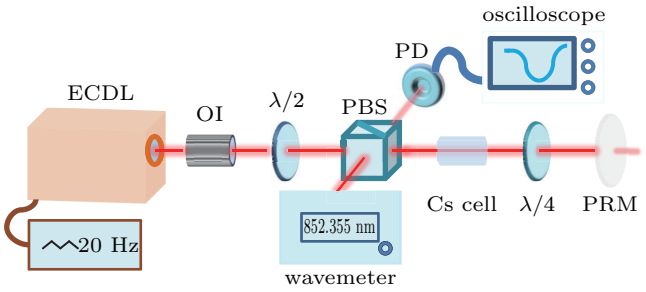


Fig. 5. (color online) Schematic diagram of the saturated absorption spectrum setup. OI: optical isolator; PBS: polarization beam splitter; PRM: partially reflecting mirror; PD: photodiode.

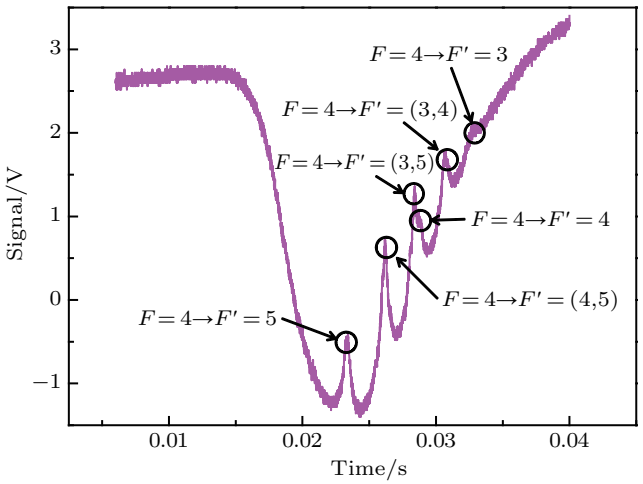


Fig. 6. (color online) The Cs $6^2S_{1/2}(F = 4) \rightarrow 6^2S_{3/2}(F' = 3,4,5)$ saturated absorption spectrum with Doppler background.

The ECDL wavelength was tuned to 852.355 nm, close to the D2 line of the Cs by adjusting the temperature and current. The corresponding temperature and current for 852.355 nm are 28 °C and 54 mA, respectively. Then the laser current was modulated at a frequency of 20 Hz and an amplitude of $\sim$ 80 mV with a peak to peak triangular signal, to sweep all six peaks of the saturated absorption spectrum. We note here that the detected light intensity must be much smaller than the

pumping light intensity and their opposite paths of propagation must be overlapped.

The saturated absorption spectrum of the $\lambda = 852.355$ nm $6^2S_{1/2}$ to $6^2S_{3/2}$ transition in Cs is shown in Fig. 6. All six absorption peaks are observed clearly, indicating that the ECDL output frequency is stabilized at 852.355 nm.[6]

Then a commercial laser with high frequency stability was used to evaluate the ECDL frequency stability through the beat note signal of the two lasers. The ECDL is locked on the peak $F = 4 \rightarrow F' = 5$ of the saturated absorption spectra and the reference laser is stabilized on the crossover peak $F = 4 \rightarrow F' = (4,5)$ between $F = 4 \rightarrow F' = 5$ and $F = 4 \rightarrow F' = 4$, leading to a frequency difference of 125 MHz between the two lasers. The resulting beat note signal is then counted by the SR620. Figure 7 shows the frequency stability of the ECDL derived from the Allan standard deviation.

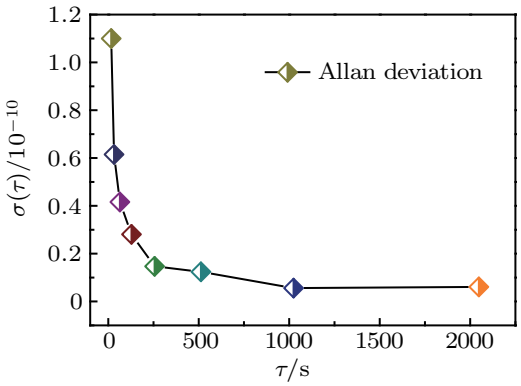


Fig. 7. (color online) The frequency stability of the ECDL derived from the Allan standard deviation.

As can be seen from Fig. 7, the frequency stability was improved as the integration time increased. A maximum long term stability of up to 5.59×10^{-12} was achieved at the integration time of 1024 s. The frequency stability was stable for a wide range of integration times from 1024 to 2048 s, exhibiting an excellent frequency stability for this type of ECDL structure.

4. Conclusion and perspectives

In conclusion, a narrow linewidth for the ECDL was realized by using a broad bandwidth interference filter. The measured Lorentzian linewidth of the ECDL was 95 kHz and the spectral purity was 2.9 MHz. The ECDL demonstrated a long-term frequency stability as high as 5.59×10^{-12}. This type of ECDL has a simple structure, with associated low costs and a high performance, indicating a promising potential for this design.

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