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Dual-wavelength bandwidth-narrowed output of a high-power diode laser using a simple external cavity

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ABSTRACT Using an external cavity consisting of an etalon and a mirror, dual-wavelength operation of a high-power broad-area multi-stripe diode laser is achieved. The reflection of the etalon is used as the output beam of the system. The free-running bandwidth of the laser diode is about 2.0 nm. At dual-wavelength operation, the bandwidth of each wavelength component is narrowed to about 0.07 nm, while the space between them is 1.65 nm, determined by the FSR of the etalon. We obtain an available dual-wavelength output power of 2.0 W at the drive current of 6.5 A. The power ratio of the components at two different wavelengths can be changed by changing the temperature of the diode laser. To tune the wavelength of the dual-wavelength output, the temperature of the laser diode and the tilt angle of the etalon are changed simultaneously

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1 Introduction

The high-power laser diode (HPLD) has been widely used in optical communications, solid-state laser pumping, material processing, and scientific research. However, free-running HPLDs operate with a wide bandwidth (typically ∼ 2 nm). In several applications, such as the laser cooling and trapping of atoms and frequency-doubling, a high coherence length is required. For the purpose of bandwidth narrowing, several injection-locking techniques have been developed. Up to date, there are mainly two injection configurations. One is the so-called master-injection. The HPLD is injection-locked to a lower-power single-mode diode laser [1–6]. The other is referred to as self-injection. A mode-selective feedback is generated by an external cavity [7–12].

Tunable dual-wavelength laser diodes are of interest to numerous scientific and practical applications such as wavelength-division-multiplexed communications, optical sensing, optical switches, optical signal processing and optically pumped mm-wave generation. Laser diodes have achieved dual-wavelength operation in several approaches [13–17]. Simultaneous operation at three different wavelengths has been demonstrated at relatively low output powers [18]. Compared to other dual-wavelength laser sources, diode laser sources are very attractive because of the availability of laser diodes operating within different wavelength regions, and the possibility to coarsely shift the operating wavelength by changing the operating temperature. Therefore, for applications like e.g., DIAL remote sensing where one of the two wavelengths needs to be matched exactly to a given absorption line, alternative laser sources may be difficult to find.

We have achieved bandwidth narrowing of a HPLD by a phase-conjugated injection with a special mutually pumped phase-conjugator [19] and tunable bandwidth narrowing by a simple external-cavity with an etalon and a grating [20]. In this paper, we report the performance of tunable dual-wavelength operation of a HPLD using an external cavity consisting of an etalon and a mirror. The difference between the two operating wavelengths is 1.65 nm, given by the FSR of the etalon. The bandwidth of each wavelength component of the dual-wavelength output is about 0.07 nm, and the available output power of the system is 2.0 W.

2 Experimental setup

The experimental setup is shown in Fig. 1. The HPLD is a SLI-CW-SLD-C1-808-7M-R consisting of three initially uncoupled stripes with the emitter dimensions of 1 µm × 200 µm for each stripe. It operates at a tunable center wavelength of about 808 nm with a full bandwidth of about 2 nm. The threshold drive current I_{thr} of the HPLD is 1.8 A.

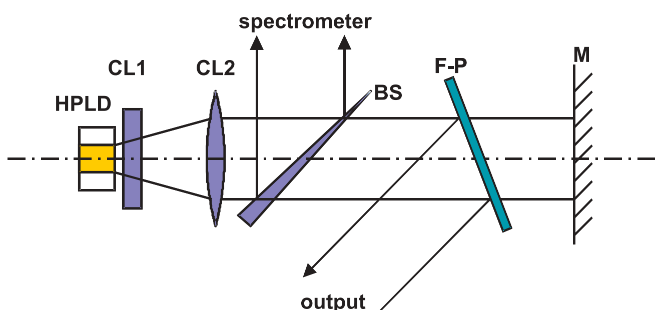

FIGURE 1 Experimental setup for self-injection locking. LD1, SLI-CW-SLD-C1-808-7M-R, CL1, micro-cylindrical lens, CL2, cylindrical lens with $f = 124$ mm, BS, beam splitter (wedge), F-P, Fabry Perot etalon with thickness of 140 µm, M, mirror

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This laser diode is no longer commercially available, but we are certain that our results are valid for other laser diodes as well, as the SLI diode is a standard device and not especially designed for dual-wavelength operation. The laser beam is collimated by a cylindrical micro-lens CL 1 in the fast axis and another cylindrical lens CL 2 with a focal length of 124 mm in the slow axis, respectively. The initial power of the free-running diode was 7 W. But because of long-term use, when we did the experiments, it had decreased to only 2.3 W after the collimation lenses at 6.5 A operating current.

A wedge is used as a beamsplitter to reflect a weak sub-beam into a spectrometer to record the operation longitudinal mode by a line CCD array with high dynamic range. The line CCD is read out into a PC using an internal 12-bit A/D converter of the camera. The resolution of the spectrometer using this camera was 0.015 nm. A mirror is used to build up an external cavity, in which a F-P etalon with a thickness of 140 µm and a Finesse of about 40 is inserted to select the wavelength of the feedback light. The reflection from the etalon is used as the output of this system. A part of the output beam is also aligned into the spectrometer, so that the spectra of the feedback light travelling back to the laser diode and of the output beam can be investigated simultaneously using a standard 2D CCD camera, but at a lower resolution (approximately 0.05 nm).

3 Experimental results and discussions

Figure 2 shows a typical bandwidth narrowing result. When the HPLD is running freely, the full bandwidth is about 2 nm (the dashed line in the lower part of Fig. 2). With the seeding light supplied by the mirror and wavelength-selected by the F-P etalon, free spectral range (FSR) is about 1.65 nm, the HPLD wavelength is locked and dual-wavelength operation with a wavelength space of 1.65 nm is obtained. The bandwidth of each peak is about 0.07 nm. As the wavelength difference between two longitudinal modes is approximately 0.11 nm, this shows that each peak mainly consists of only one longitudinal mode. However, there are several transverse modes oscillating simultaneously which cause the bandwidth of the peaks to be in the same magnitude as the frequency interval to the adjacent side modes, and therefore weak sidemode contributions may be contained in the line profile. At $I = 3.6 I_{th}$, the highest available drive current in our experiment, we obtain a dual-wavelength output of 2.02 W. The power stability of the output beam in 3 hours is better than 2%, while the spectral stability in 3 hours is better than 3%, depending mainly on the temperature stability.

It is worth pointing out that the power ratio of the components at two different wavelengths can be changed by changing either the temperature of the HPLD, or the tilt angle of the F-P etalon. Even, one can easily change the operation of the HPLD between single- and dual-wavelength simply by changing the temperature, as shown in Fig. 3. At the beginning, the temperature of the HPLD is selected to achieve dual-wavelength operation with equal power at each wavelength. When increasing the temperature to red-shift the free-running spectrum, we observe that the power of the longer wavelength component increases while that of the shorter wavelength component decreases, and finally single-wavelength operation is achieved. Similarly, by decreasing the temperature of the HPLD, one can also obtain single-wavelength operation at the other wavelength.

The spectra of the light emitted by the diode laser with and without external feedback are measured using an intra-cavity beamsplitter and compared with the spectra of the output, which is created by reflection at the etalon. The spectra are shown in Fig. 2. Usually injection locking by an external cavity can be considered an amplification process of seeding light, and it might be expected that the spectrum of the light reflected out by the F-P should exhibit a dip at the wavelength the laser is actually operating at. When the optical path to the feedback mirror is blocked, the effect of the wavelength-dependent reflectivity of the etalon is indeed observed in the spectrum of the free-running laser diode reflected at it (shown as dashed line curve in upper part of Fig. 2). The spectrum of the output obtained when the diode is operated with external cavity feedback, however, did not exhibit such a dip. We have also observed that there is a slight difference between the center wavelengths of the light emitted by the HPLD while the

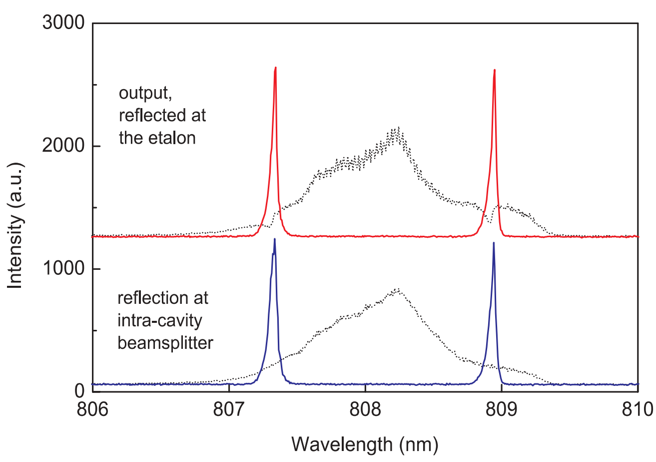

FIGURE 2 Spectra of the HPLD with and without the external cavity. *Upper part*: Light reflected at the F-P etalon, corresponding to the output of the system. *Lower part*: Light reflected at the beamsplitter. The *solid line* is obtained when the feedback of the external cavity is applied to the laser diode. The *dashed line* is obtained when the optical path to the mirror M is blocked

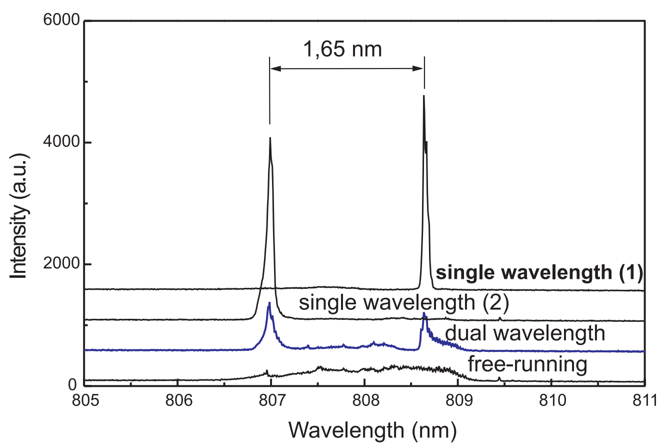

FIGURE 3 By changing temperature, the HPLD can operate at single- and dual-wavelength with a bandwidth of only about 0.07 nm

feedback is applied to it and the wavelength of the output of the total system, which is generated by reflection of that light by the F-P etalon, respectively.

To understand this effect, we have simultaneously measured the spectra of the light travelling from the HPLD towards the feedback mirror using the reflection at a beam splitter (as shown in Fig. 1), and of the light travelling from the external cavity back towards the HPLD by investigating the reflection at the back side of the same beamsplitter. The result is shown in Fig. 4. Apparently, the bandwidth of the feedback seeding light is broadened in the direction of long wavelength during amplification by the HPLD, thus the center-wavelength is red-shifted, as we have also observed in previous experiments [20]. This shift is about 0.02 nm in our experimental measurements. The light travelling from the HPLD towards to the mirror is split into two parts at the F-P etalon. The first part is the light transmitted by the etalon, corresponding to the original seeding wavelength. The second part is reflected out by the etalon, because it has a slightly longer wavelength corresponding to the observed red-shift between the seed light and the output of the HPLD. As a result, there is a red-shift of 0.02 nm between the wavelength of highest transmission of the etalon and that of the output of the locked HPLD, created by reflection at the etalon.

When the drive current is increased from the threshold ($I_{th} = 1.8$ A) to the available operation current of 6.5 A (corresponding to $3.6 I_{th}$), the HPLD can run always at dual-wavelength operation, as shown in Fig. 5. Because higher currents correspond to higher temperatures of the *p-n* junction of the HPLD, for obtaining the spectra shown in Fig. 5 the tilt angle of the F-P etalon needed to be adjusted to match the spectrum of the HPLD at each current. It should be pointed out that, at a certain drive current, one can tune the dual-wavelength operation by changing the temperature of the HPLD and adjusting the tilt angle of the F-P etalon simultaneously.

In our experiments, the highest current of the power supply is 6.5 A, i.e., $3.6 I_{th}$. From Fig. 5 it is reasonable to expect that at higher currents than 6.5 A, it is also possible for the HPLD to work at dual-wavelength operation. Because the

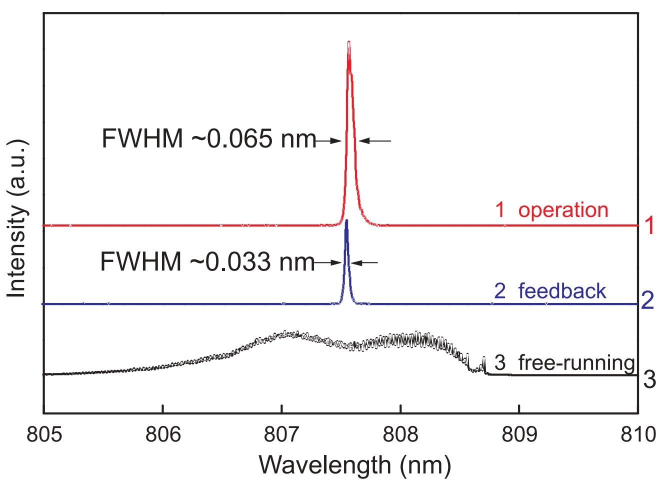

FIGURE 4 The bandwidth broadening and the red-shift between the center wavelength of the injection beam and that of the output of the HPLD. The resolution of the spectrometer was 0.015 nm

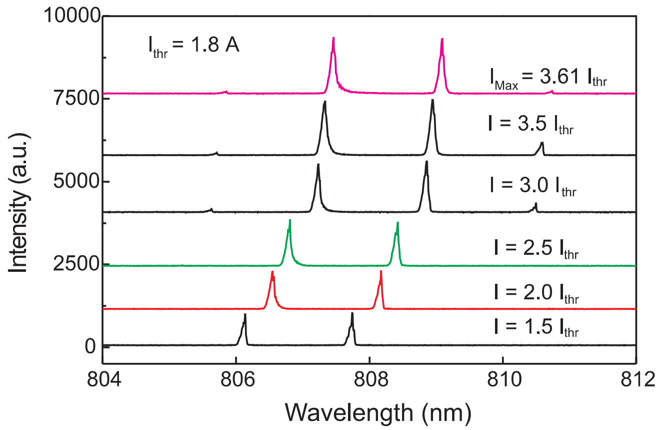

FIGURE 5 The spectra of the HPLD operating at dual- wavelength at different drive currents

HPLD has been used experimentally for a long time, a serious decay has happened, and the output power is much lower than it should be. If used a new HPLD, the available output power will be much higher than 2.0 W. On the other hand, the output surface of the HPLD used in our experiments is not anti-reflection coated. We assume that if it was anti-reflection coated, the bandwidth of each wavelength component will be narrower than 0.07 nm. The FSR of the F-P etalon we used is 1.65 nm. We believe that if we use an etalon with smaller FSR, one can achieve multiple wavelength operation with more than two wavelengths, because in this case more transmission maxima of the etalon would be enclosed within the gain profile of the laser diode.

The beam quality of the SLI laser diode used in our experiments was rather low. With our setup, no distinct improvement beam quality was obtained as there were no components limiting the number of transverse modes in the cavity. However, we believe that tapered laser diodes which are capable of emitting several Watts of output power at remarkably high beam quality ($M^2 < 2$) [21, 22] can be deployed in our external cavity arrangement without losing beam quality because it does not exhibit transverse mode selectivity.

The wavelength of the laser diode we have used is somewhat too low to use the device for DIAL measurements at the 820 nm water vapour absorption lines, as the wavelength tuning coefficient with temperature is 0.27 nm/K, and therefore the overall tuning range is limited to several nm. However, using tapered diode lasers in the 940 nm region [22] an excellent source in region of the 935 nm absorption lines should be obtainable.

4 Conclusions

We have demonstrated a HPLD operating at dual-wavelength with a simple extra-cavity consisting of an etalon and a mirror. At the drive current up to as high as 3.6 times the threshold, we obtain a bandwidth-narrowed dual-wavelength output with the effective output power of the system of 2.0 W. The wavelength space is 1.65 nm, determined by the FSR of the etalon. The bandwidth of each wavelength component is about 0.07 nm. The power ratio of the components at two different wavelengths can be changed by changing the temperature of the HPLD. To tune the wavelength of the dual-wavelength output, one can adjust the temperature and the tilt angle of the etalon simultaneously.

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