Injection Locking of Individual Broad-Area Lasers in an Integrated High-Power Diode Array

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Abstract

We have performed an experiment on the injection mode-locking of each individual multi-mode broad-area high-power laser in a bar of 19-laser array using a single-mode laser as the source of injection. It has been found that a broad-area laser with 1 W output power can be injection-locked to a single mode with less than 0.5 mW of injection power. The injection-locked broad-area laser shows very narrow line width regardless of the output power. It seems that the matching of the injection wavelength to one of the free-running modes of all lasers in the array is an essential and necessary condition for achieving mode locked coherent operations in the whole array.

High-power broad-area laser diodes have received increasing attention in applications of material processing, laser spectroscopy and pumping, and optical communications due to their compactness, low cost, and high efficiency. Up to date, a broad-area laser diode can provide output power up to 100 watt. These lasers are not coherent, the inherent features of this type of lasers include broad spectrum and poor beam quality. To achieve coherent operations in these lasers, optical injection [1-5] and external cavity [6,7] techniques have been used to control their spectrum and beam qualities. A number of recent experiments have demonstrated the improvement of beam quality and spectral width of the broad-area laser diodes. For example, the injection locking of one single broad-area laser of an aperture up to 100 μm $\times$1 μm and a maximum output power up to 840 mW has been demonstrated [3-5].

In this paper, we report experimental results on the injection mode-locking of each individual multi-mode broad-area high-power laser in a bar of a 19-laser array (see inset of Fig. 1) using a single-mode laser as the source of injection. Each broad-area laser in the array has a cavity length of 1 mm and an emitting aperture of 150 μm$\times$1 μm and is capable of emitting a maximum output power over 1W. The separation between any two adjacent lasers in the array is 500 μm and the total length of the array is 1 cm. We demonstrate that with less than 0.5 mW of injection power into each one of the 19 lasers, 1 W of single-mode coherent output power can be obtained. Injection locking

occurs at different drive current regimes where the free-running frequency of the broad-area laser matches the injection frequency. The optical spectrum of the injection-locked broad-area lasers shows a very narrow bandwidth similar to the injection laser regardless of the output power. The influence of the frequency matching between the injection light and the slave laser as well as the locking range have been investigated, which heuristically indicates that there might be a way to synchronize the whole broad-area laser array with injection locking.

The experimental setup is shown in Figure 1. The broad-area laser is chosen from a Coherent B1-20C laser diode array in the experiment. The overall aperture of $1\text{cm} \times 1\ \mu\text{m}$ of the laser array emits a far-field pattern subtended by $6° \times 50°$. We use two cylindrical lenses (L1 and L2) with appropriate focal lengths to collimate the output beam from the laser array. The light output of the laser array passes through two collimation lenses (L1 and L2) and is selected by a thin slit. The spectrum of each broad-area laser can be measured with an optical spectral analyzer and a Fabry-Perot super cavity.

The single-mode master laser used in this experiment is a wavelength-tunable laser diode (TOPTICA DL-100) with a maximum output power of 100 mW. The wavelength is tunable between 800 and 810 nm with an external grating. An optical isolator with an isolation of 60 dB is used to block light reflecting back into the master

laser. An optical attenuator and a half-wave plate are used to respectively adjust the power and the polarization of the injection light.

For the drive current well above the threshold, each broad-area laser exhibits multiple longitudinal modes. The mode separation is measured to be 0.08 nm for all lasers. The dependencies of the wavelength on the drive current and the temperature are measured to be 0.03 nm/A and 0.07 nm/K, respectively. In this experiment, we utilize these dependencies and tune the central wavelength of the broad-area laser by adjusting the drive current (with an accuracy of 0.01 A) and/or the temperature (with an accuracy of 0.01 K).

Fig. 2 shows the experimentally measured lasing wavelength span for all 19 lasers in the array. The free-running wavelength span is determined from the optical spectrum as a range of wavelength within 10 dBm of the peak wavelength. The drive current of the laser array is at 11 A and the corresponding output power is around 150 mW. It can be found from Fig. 2 that, within the spectral bands between 806 nm and 810 nm, the longitudinal modes of the 19 lasers are different from one another due to the inhomogeneous nature of the broad-area lasers. Optical injection has been conducted for all 19 lasers. The small rectangles in Fig. 2 shows the injection wavelengths to which each individual laser was locked. In this measurement, we have employed two injection wavelengths: 807 nm and 808.6 nm. In achieving the injection locking, the

drive current of each laser is slightly tuned to obtain the optimum injection efficiency.

In the following, we choose to describe the injection locking of a particular laser, LD#7, in the array to respectively illustrate the injection locking performance. The threshold drive current of this laser is around 8.5 A at 25.0°C. The wavelength of the injection light is 808.75 nm and the injection power measured at the point 'A' of Fig. 1 is about 4.8 mW. First, we investigate the variations of the spectral structure of LD#7 when the drive current is changed. We found that the injection locking performance strongly depends on the drive current of the laser array. Successful injection locking occurs only at several discrete regions of the drive current levels of I_d=8.5, 11.2, 13.8, 16.6, 19.3, and 22.0 A. Figure 3 shows the spectra of LD#7 before and after the optical injection for these drive currents. All spectra are normalized with the same scale. We have observed that (a) a broad spectrum of the laser in the absence of the optical injection and (b) a sharp single-mode operation of the laser after successful injection locking. Note that, at I_d=8.5 A, the light output is very weak since the laser emits near its threshold. At some drive currents, weak side-mode peaks are observed, indicating a non-perfect injection locking of the laser. The output powers of the LD#7 at these six drive current levels are 15.4, 164, 361, 593, 816, and 1040 mW, respectively. There is no significant change in the overall light output power of LD#7 with and without the injection locking. This implies that the power of the laser is mainly focused to a single

longitudinal mode due to injection locking.

The optical spectrum of the injection-locked broad-area laser is measured with a Fabry-Perot super cavity (FSR 6GHz, resolution < 6 MHz). Figure 4 shows two typical optical spectra of the broad-area laser #7 after the successful injection locking. We have measured and found that the spectrum bandwidths of the injection-locked laser corresponding to the drive currents in Fig. 2, i.e., I_d=8.5, 11.2, 13.8, 16.6, 19.3, 22.0 A, are 8, 8, 9, 12, 10, and 8 MHz, respectively. These bandwidths nearly equal to the linewidth of the injection laser which was measured to be 7 MHz. The result clearly showed that an injection-locked broad-area laser has a very good single-mode behavior which is almost independent of its drive current or output power.

The mechanism for the above observations that the successful injection locking occurs at some particular values of the drive currents can be explained as follows. Based on the measurements of the mode separation of the laser (0.08 nm) and the wavelength dependence on the drive current (0.03 nm/A), we know that the drive current increment required for shifting the lasing spectrum the amount of the mode separation (0.08 nm) is about 2.67 A. Therefore, at each point of the drive current observed in the above experiment, there might exist one longitudinal mode of the broad-area laser that is very close to the injection frequency. The match between the injection light frequency and one of the longitudinal mode frequencies of the broad-area laser maximizes the injection

efficiency and hence results in the optimum injection performance. In some lasers, we observed several different sets of the drive currents for successful injection locking. Since the broad-area laser has multiple lateral modes, the different sets of drive current may correspond to the different lateral modes that have slightly different optical frequencies.

The locking range around each optimum drive current of the broad-area laser depends on the injection strength. As an example, we measured the locking frequency range versus the injection power for LD#7. The results are plotted in Fig. 5. Note that the injection strength here is defined as the square root of the injection power measured at the location after the attenuator in Fig. 1. In general, the locking frequency range is linearly dependent on the injection strength. Furthermore, the injection-locking domain is not symmetrical with respective to the frequency detuning. There exists a negative frequency shift which is considered due to the linewidth enhancement factor of the semiconductor laser. Both of the above properties are consistent with the injection characteristics of single-mode laser diodes [8].

Now we briefly discuss the possibility of synchronizing the broad-area laser array with optical injection. We have conducted experiments on injection locking of all individual broad-area lasers in the array and found similar phenomena and results as described above. In general, the injection locking of a broad-area laser depends on two

issues: (1) wavelength matching between the injection frequency and one of the longitudinal modes of the broad-area laser in the free-running state, and (2) injection power needed to achieve the mode locking. Our experimental results in Fig. 3 clearly show the successful injection locking of a broad-area laser at a very high drive current, i.e., at a very high output power. The spectrum of the injection-locked laser does not depend on the drive current. For the experimental results of Fig. 2, the injection power measured after the beam splitter (point 'A' in Fig. 1) is about 4.8 mW. The spot size of the injection beam in front of the laser array is calculated to be about 100 μm $\times$10 μm. Since the thickness of the laser emitting area is only 1 μm, the actual injection power inside the cavity was estimated to be less than 0.5 mW. Therefore, it is possible to lock a broad-area laser array with each individual laser output power up to one watt in a single longitudinal mode.

In conclusion, we have experimentally demonstrated that it is possible to injection lock a broad-area laser array with a moderate injection power. Injection locking of one broad-area laser with the output power up to one watt has been experimentally shown and the parameter influence including the locking range have been investigated. The results are very important in the practical application of the injection locking technology to high-power broad-area lasers. Our experiments suggest the feasibility of achieving high intensity diffraction limited coherent radiation from an

array of broad-area lasers.

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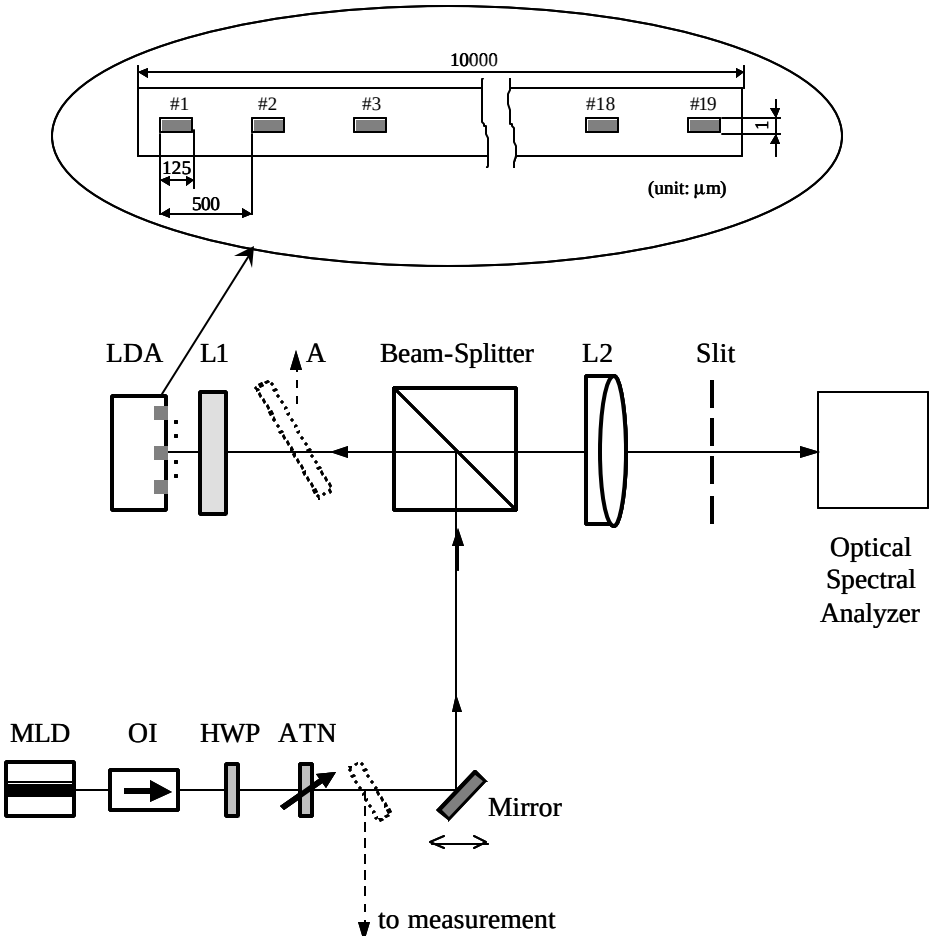

Fig. 1 Schematic of experimental setup. LDA: laser diode array, LDM: injection laser diode, L1: fast-axis cylindrical lens, L2: slow-axis cylindrical lens, OI: optical isolator, HWP: half-wave plate, ATN: attenuator. Inset box: configuration of the 19-laser array.

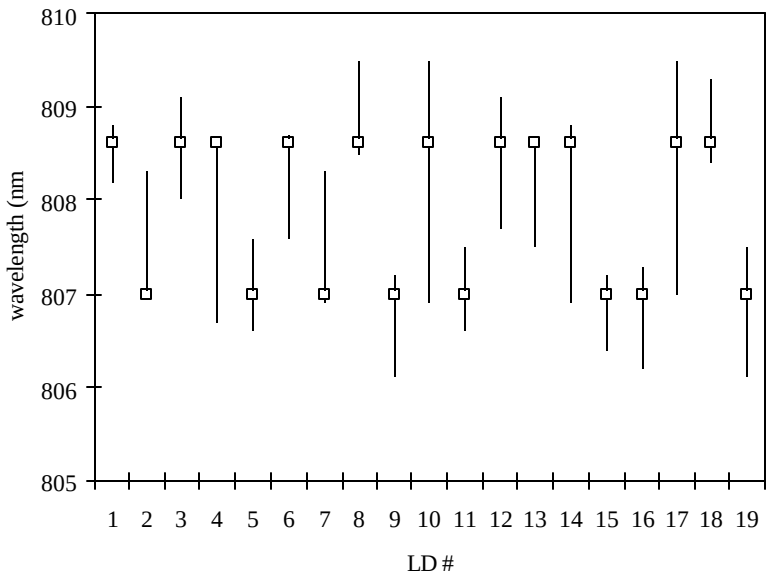

Fig. 2 Free-running wavelength span of all 19 lasers in the array are represented by vertical bars. The rectangles mark the injection wavelength at which each laser was locked. The drive current I_d is approximately 11 A.

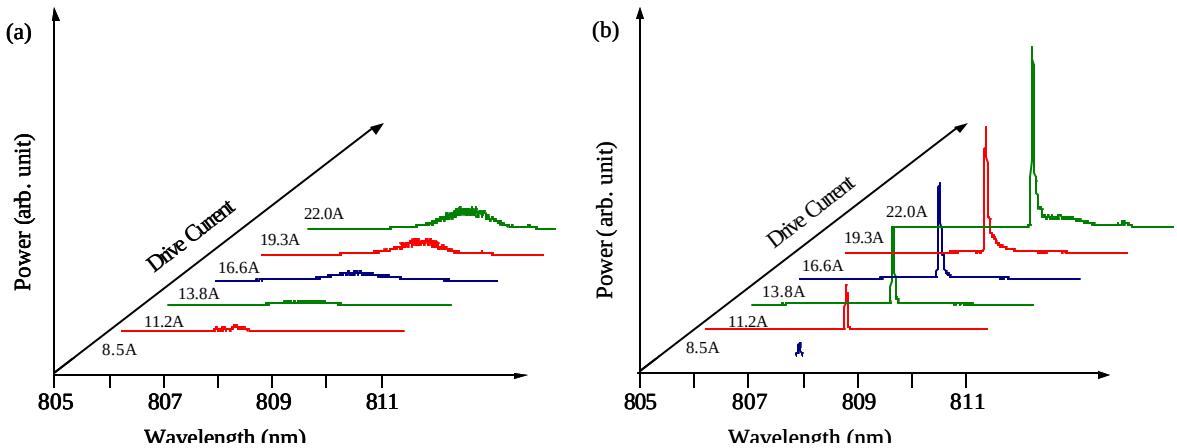

Fig. 3 Optical spectra of LD#7 at different pumping levels. (a) Spectrum of free-running state and (b) spectrum at injection locking.

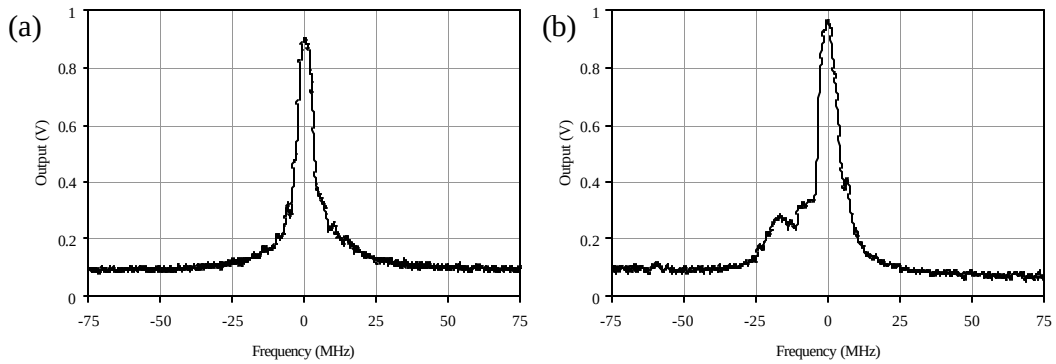

Fig. 4 Optical spectrum of injection-locked broad-area lasers measured with a super cavity. (a) I_d=11.2A, (b) I_d=22.0 A.

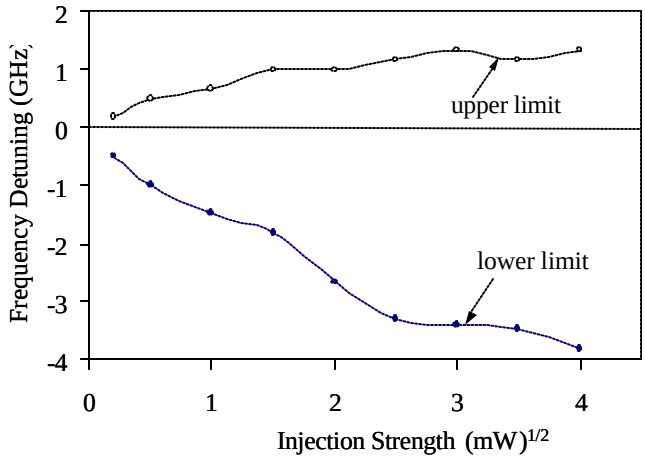

Fig. 5 Injection-locking range versus the injection strength.