Broad-Area Laser Array Synchronization Using External Cavity

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ABSTRACT

We present experimental results on the locking of a 19-broad-area semiconductor laser array using a novel design of external cavity containing a lens array, projection optics, and a diffractive grating. All lasers are locked to single longitudinal mode. Significant improvement of the spatial profile of the entire laser array output beam has been observed. The center lobe of the far-field pattern of the laser array shows a single wavelength which can be tuned over a range more than 10 nm. The proposed technology can be applied to larger arrays including the stacked arrays.

Keywords : semiconductor laser, laser array, broad area laser, locking, high power, external cavity, optical feedback, grating, lens array

1. INTRODUCTION

Over all types of lasers, semiconductor lasers are most compact and have inherently the largest electrical-optical conversion efficiency, which considerably reduces power requirements as well as the thermal/load burden on the operation platform. Today, a stacked array of broad-area semiconductor lasers with an overall emission aperture size less than one square inch can readily provide kilowatts of output power. The limitation of such lasers is their poor beam quality and broad spectrum.

Synchronization and coherent beam combination of broad-area lasers provide a promising method of obtaining high power and high beam quality laser outputs.[1] A variety of techniques have been proposed to synchronize broad-area lasers and laser arrays. These involve primarily optical engineering efforts such as master optical power amplifier (MOPA) scheme[2], injection locking of laser arrays[3,4], phase locking of laser arrays using an external reflector[5-7], and spectrum beam combining using external grating[8].

In this paper, we report experimental results on the synchronization of an integrated broad-area laser array using an external cavity with a lens array, projection optics, and a diffractive grating. A commercially available broad-area laser array is used in the experiments. Each broad-area laser in the array has an emission aperture of 125 μm×1 μm and is capable of emitting a maximum output power over 1W. The separation between two adjacent lasers in the array is 500 μm and the total array length is 1 cm. In our previous work, we demonstrated the locking of both longitudinal and transverse modes of such lasers using optical injection from a single mode laser.[9,10] In this experiment, we demonstrate the laser array synchronization using an external cavity. Each laser emitter is separately collimated with a cylindrical lens array that is designed to match the laser array configuration. By appropriately locating the lens array, the laser array output is split into two beams at different angles with adjustable power ratio. One output beam from the array is fed back from a diffractive grating in a Littrow configuration through a telescope in the external cavity. The other beam is used as the array output. Experimental results show that all lasers are frequency-locked over the entire pumping current range from the threshold (~ 9 A) to 22 A where the output power of the laser array exceeds 20 W. The far-field pattern of the laser array shows

significant improvement in terms of the energy ratio in the center lobe. The wavelength of the array output can be tuned over 10 nm with the side mode suppression ratio larger than 25 dB.

2. EXPERIMENTAL DESIGN

Fig. 1 shows the schematic of our experimental setup. The laser array used in this experiment has 19 InGaAsP broad-area laser diodes with a maximum total output power over 20 W. The entire array is driven with a common current source. Each broad-area laser emitter in the array has a cavity length of 1 mm and an emitting aperture of 125 μm×1 μm and is capable of emitting a maximum output power over 1W. The separation between two adjacent lasers in the array is 500 μm and the total width of the array is 1 cm. At the free-running state, all lasers have multiple longitudinal and transverse modes. The longitudinal modes of the 19 lasers spans over a wide range of 806 - 811 nm.

Since the broad-area laser emitter has a very asymmetric emission aperture (125 μm×1 μm), the laser output shows different beam qualities along fast and slow axes. Along the fast axis direction, the emission size (~ 1 μm) is close to the laser wavelength (around 0.8 μm) and the output beam shows a fundamental Gaussian mode with a large divergence angle. The beam collimation along the fast axis is conducted by a gradient index (GRIN) cylindrical lens with a very short focal length (1.3 mm) and large numerical aperture (0.5). Along the slow axis direction, the emission size (125 μm) is much larger than the laser wavelength and the output beam exhibits higher order modes with multiple lobes in the far-field pattern. Control of the transverse mode along the slow axis direction is required to achieve the single mode operation. In this experiment, we use a micro cylindrical lens array (GRINTECH) to collimate the array output in the slow-axis direction. The separation between each lens is designed to match the laser array. The whole lens array consists of 28 micro cylindrical lenses assembled in an array bar with a dimension of $14 \times 0.7 \times 1.3$ mm^3. Both fast axis collimation lens and slow axis lens array have AR coating around 810 nm.

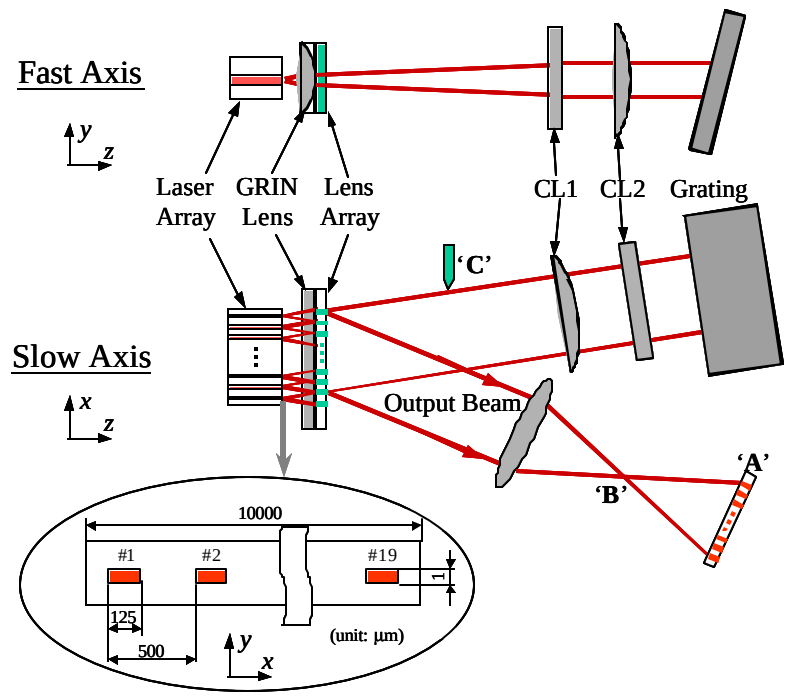

Figure1 Schematic of experimental setup. External cavity part is shown at both slow- and fast-axis directions. Inset box: configuration of 19-emitter broad-area laser array (Coherent Inc.).

In the experiment, we use the slow-axis lens array as a beam splitter to divide the laser array output into two portions with an adjustable ratio. To this end, we shift the lens array along the *x* direction in Fig. 1. Fig. 2 shows the far-field intensity distribution of the laser array output along the *x* direction. When the position of the lens array matches exactly that of the laser, more than 95% of the laser array output is focused in the central lobe as shown in Fig. 2(a). When the lens array shifts 250 μm relative to the laser array, two central lobes appear at the far field with roughly equal intensity as shown in Fig. 2(b). The angle between two lobes is about 14°. The light intensity in the rest lobes of Fig. 2 is less than 5% of the total output. The ratio between the two main lobes can be continuously tuned from 0.1 to 10 by shifting the lens array along the slow axis.

The first part of the array output beam is feedback by an external cavity as shown in Fig. 1. The external cavity consists of two cylindrical lenses and a diffraction grating (830 l/mm with the blaze wavelength of 830 nm). Both lenses have the focal length of 300 mm. The first lens collects the beam at the slow-axis direction and is located 300 mm away from the lens array. The second lens collimates the beam at the fast-axis direction and is located 50 mm from the first lens. The diffraction grating is set in a Littrow configuration with the grove vertical to the array direction. The blaze angle is about 20° and the first order diffraction beam reflects more than 95% of the incident beam. Both CL1 and CL2 are optimized based on the reflected light from the external cavity. The position of CL1 is adjusted to achieve the clear image of the laser array at the front of the lens array. The position of CL2 is optimized according to the best locking performance.

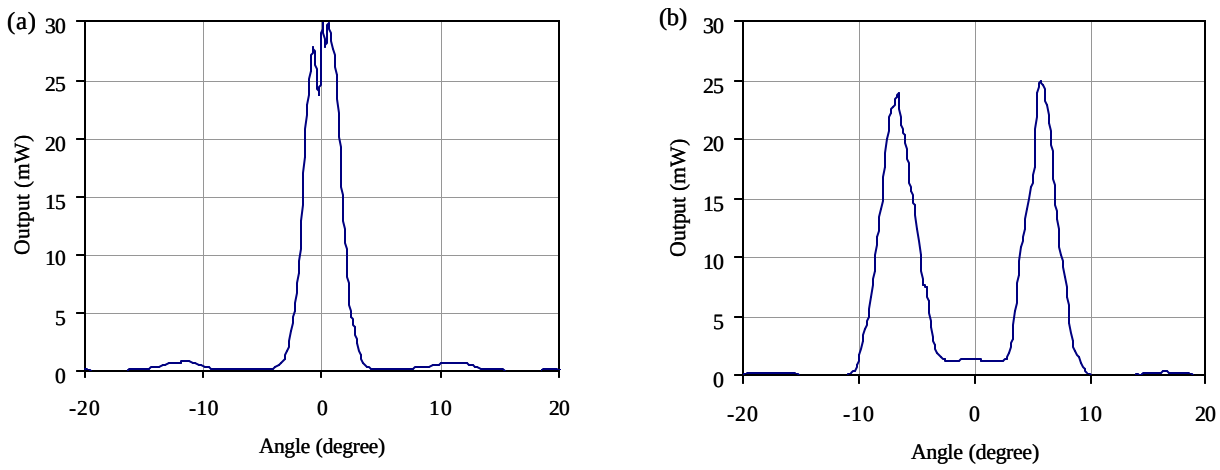

Figure 2 Far field intensity distribution of the laser array after the lens array at different conditions. (a) Lens array position matches laser array and (b) lens array is shifted 250 μm (half of the array separation) relative to (a). In both situations, more than 95% of the laser output is concentrated in the main lobe(s).

The second part of the array output is employed as the array output. Both the optical spectrum and the spatial beam properties are measured at two locations: 'A' and 'B' in Fig. 1. Location 'A' shows the image of the laser array where the light output of each individual laser emitter can be characterized separately. Location 'B' is a focused laser array output where the collective property of the laser array output is evaluated. At each location, a part of the beam is collimated into an optical fiber for a on-line monitor/measurement of the laser spectrum with an optical spectrum analyzer.

The present experimental design has a number of advantages compared to previous experiments[11-13] with external grating feedback. First, by using a lens array to split the laser output beam, no beam splitter is needed in the external cavity and the laser power loss can be avoided. Second, the feedback strength can be easily controlled in a large range through the continuous adjustment of the ratio between two lobes of the array output beam. Besides, the injection beam width and the incidence angle of the re-injection (feedback) beam can be easily adjusted by controlling the shift of the slow-axis lens array. It is well known that the far-field distribution of an injection-locked broad-area laser strongly depends on the injected-beam width and incidence angle.[3]

3. EXPERIMENTAL RESULTS

3.1 Wavelength Locking of Individual Laser Emitters

Fig. 3(a) shows the optical spectra of all 19 laser emitters at the free-running state measured at the location 'A'. Each laser is lasing at a different center wavelength with the bandwidth about 1 nm. Fig. 3(b) shows optical spectra of all lasers operating in the presence of the external cavity. All lasers are locked to the single longitudinal mode with the linewidth about 0.1 nm. However, the locking wavelength of the laser is slightly different from each other.

A series of experiments on wavelength locking at different conditions have been conducted and from all these experiments we found that lasers at the end of the array always show different locking wavelengths from the center part.

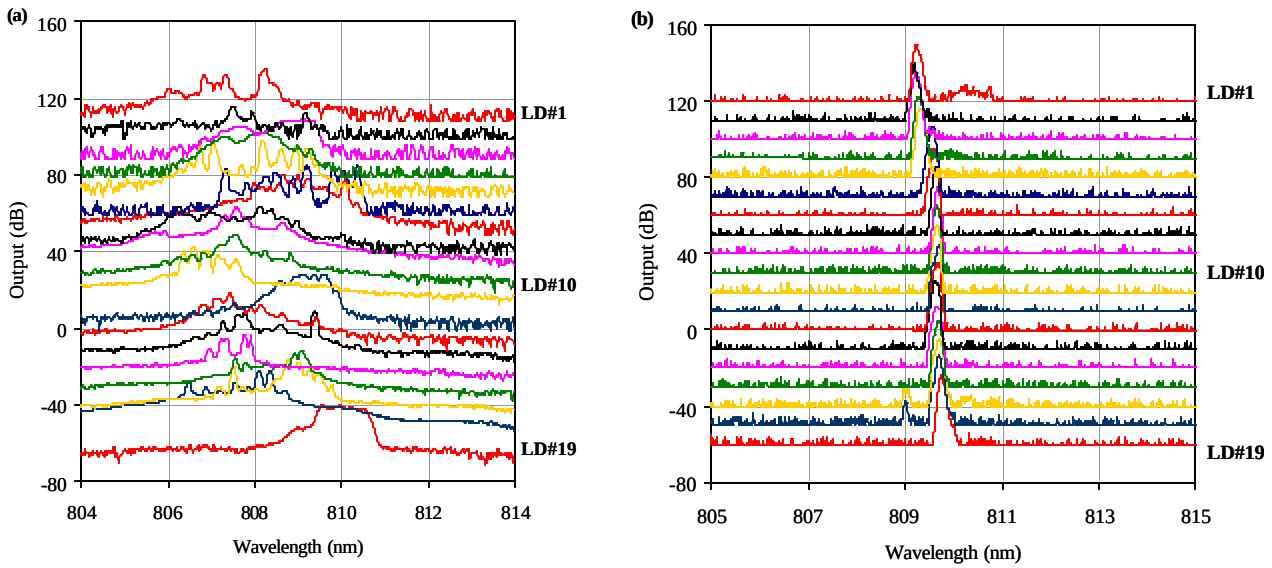

Figure 3 (a) Optical spectra of 19 emitters at free-running state; (b) optical spectra of 19 emitters with external cavity. The drive current was set at 19 A. The reference level of each laser spectrum is properly shifted for better display.

We think that the observed locking wavelength inhomogeneity is due to several factors. The first factor is the 'smile' of the laser array. The laser array used in the present experiment has the 'smile' about 7 μm. The next factor is the image aberration of the transformation optics in the external cavity, especially the slow-axis cylindrical lens CL1. Reduction of the locking wavelength inhomogeneity due to the above factors can be achieved through the 'smile' control and aberration compensation with an appropriate design of the projection optics in the external cavity. Another possible factor is the interaction among different laser emitters in the loop of optical feedback. Although linear imaging optics employed in the experiments is able to give a one-to-one mapping of the feedback, the broadening of the each laser emitter in the slow-axis direction induces certain interactions among near neighborhood lasers. To verify this property, we conducted an experiment to check the influence of the laser interaction on the locking behavior of a specific laser. We put an edge in the feedback loop and shift the position of the edge as shown in the location 'C' of Fig. 1. A

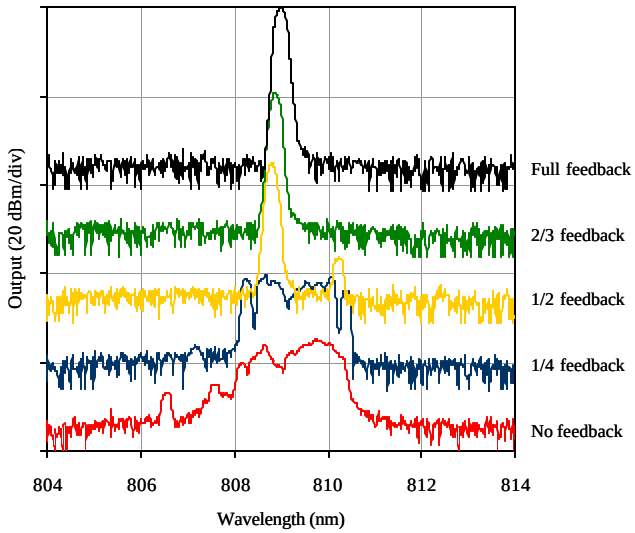

Figure 4 Optical spectrum of the laser emitter #3 at different optical feedback amounts. Reference level of each spectrum is shifted.

typical result is shown in Fig.4. The five graphs plot the optical spectrum of the laser emitter #3 at different edge positions: full feedback, 75%, 50%, 25%, and no feedback, respectively. The results show that 50% of the feedback is required in order to achieve the wavelength locking. Another indication from Fig.4 is that the amount of feedback strength affects the locking wavelength. We believe that such effect is related to the wavelength shift in Fig. 3(b) since lasers at the end side of the array receive less contribution from their neighborhoods. Further work is needed to unveil the underlying mechanism of the locking wavelength inhomogeneity.

3.2 Synchronized Laser Array Output

The total light output from the laser array is focused with a pair of cylindrical lenses at the location 'B'. Both the spatial distribution and optical spectrum are measured. First, we show the spatial distribution in Fig. 5. Two profiles plotted correspond to the light intensity distributions at the free-running state and with the external cavity, respectively. The results show that the spatial coherence is improved due to the optical feedback from the common external reflector. Spatial coherence can be further enhanced with the improvement of projection optics (to reduce aberration) in external cavity, low 'smile' and high AR-coating ratio of the laser array.

The optical spectrum of the total laser array output is also measured. Fig. 6(a) shows the free-running state optical spectrum while the Fig. 6(b) shows a series of the locked spectra. We found that the central lobe of the entire laser array output exhibits single longitudinal mode with the wavelength consistent with the center part of Fig. 3(b). The wavelength can be continuously tuned by rotating the grating. In Fig. 6(b) the wavelength of the laser array is tuned from 802 nm to 814 nm. At each case, the side mode suppress ratio is larger than 25 dB. It is noted that the laser is locked to the same wavelength when the drive current increases from the threshold value (~9 A) to 22 A.

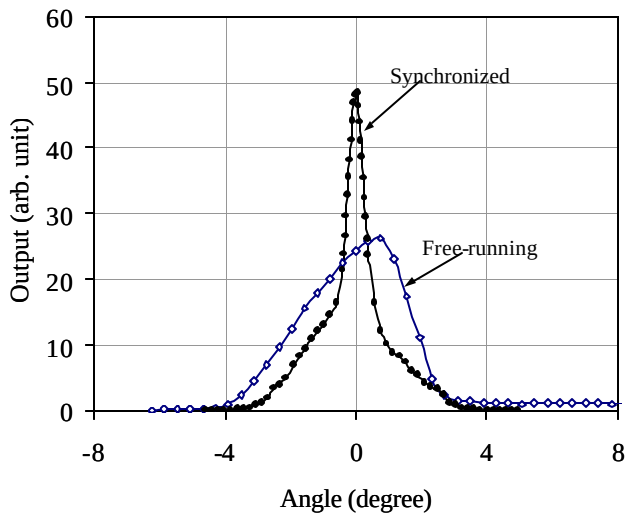

Figure 5 Far-field profile of the entire array output at the drive current of 19 A.

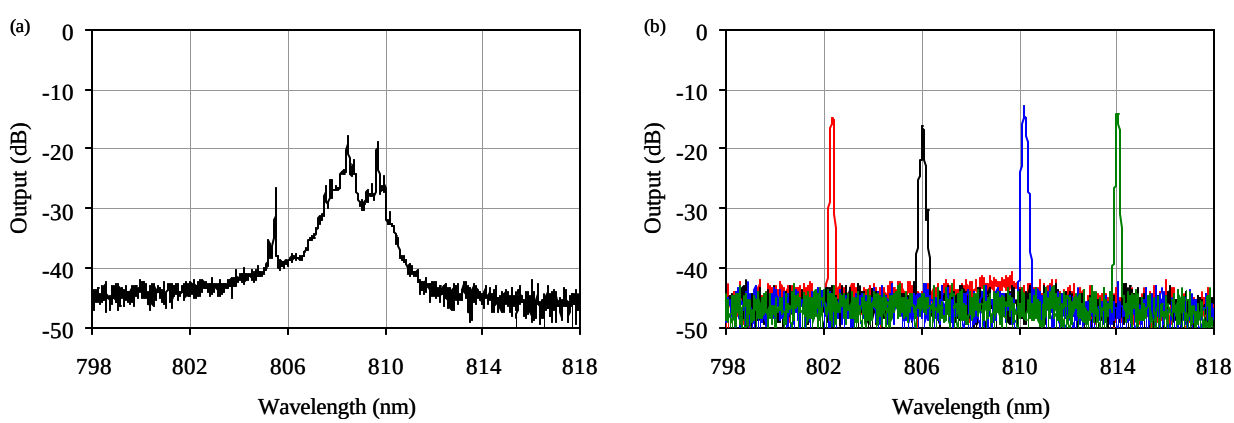

Figure 6 (a) Optical spectrum of the entire array output at free-running state; (b) Optical spectrum of the entire array output with external cavity. The wavelength is tuned from 802 nm to 814 nm. The drive current is 22 A.

4. SUMMARY

In summary, we have demonstrated synchronization of a 19-emitter high power broad-area semiconductor laser array using an external cavity with a diffraction grating. A novel collimation optical system is used to collimate and split the output beam from the laser array in a controllable manner. A part of the array output is feedback from the external grating assembled in a Littrow configuration. All 19 lasers are frequency-locked to the single mode with a narrow spectrum bandwidth. The total laser output shows much improved spatial property and single longitudinal mode with the wavelength tunable over 10 nm. The effect of the interaction among different laser emitters on the locking performance has been experimentally investigated.

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