Dynamics and Synchronization in a Broad-Area Semiconductor Laser Array with External Optical Feedback

Y. Liu and Y. Braiman

Center for Engineering Science Advanced Research
Computer Science and Mathematics Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6016

Abstract

We report experimental results on the dynamics and synchronization of a 19-broad-area semiconductor laser array in an 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. Laser coupling is investigated through the radio-frequency (RF) spectrum and temporal correlation of coupled laser emitters. Such coupling is found to exert certain effects on the frequency locking of the laser array.

1. Introduction

Synchronization of high-power semiconductor lasers has been investigated in the past two decades as a method for obtaining high output power while maintaining good beam quality. A variety of optical injection locking and external cavity techniques have been applied to lock the modes of broad-area lasers and to synchronize the laser arrays to achieve efficient beam combinations.[1] These involve primarily optical engineering efforts such as the master optical power amplifier (MOPA) scheme[2-5], injection locking of laser arrays[6-9], phase locking of laser arrays using an external reflector including the Talbot cavity[10-15], and spectrum beam combining using external grating[16]. However, to the best of our knowledge, little success has been achieved for arrays of broad-area lasers with the power levels of tenths of watts. Synchronization configuration and laser coupling are considered to be major challenges in synchronizing a high-power laser array. In addition, high power lasers are highly nonlinear system and possess a variety of complex behaviors including chaos. Therefore, it is very important to design a flexible experimental setup that is capable of dealing with both optical engineering and nonlinear dynamics aspects of the system.

In this paper we discuss our recent experiments on the dynamics and synchronization of an integrated broad-area laser array in an external cavity consisting of a lens array, projection optics, and a diffractive grating. 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 a single center lobe with a significant improvement in terms of the energy density.

Coupling among laser emitters in the array has been investigated in the above external cavity configuration. The RF spectrum shows that the strongest coupling exists between two laser emitters symmetric to the array center. The coupled lasers also show weakly-synchronized temporal waveform. Besides the direct coupling, there also exist near-neighbor coupling due to spatial broadening of the laser and the focus diffuse of the collimation optics. We investigated the effects of the laser coupling on the frequency locking performance.

2. Experimental Setup

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. Optical spectrum and beam properties of the array have been described in previous work.[17] Figure 1 shows a schematic of the experimental design. 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 cylindrical microlens (focal length f=1.8 mm, diameter D=0.5 mm, curvature radius R=1.0 mm) array to collimate the array output in the slow-axis direction. The separation between each lens is designed to match the laser array. Both fast axis collimation lens and slow axis lens array have anti-reflection (AR) coating around 810 nm.

Apart from the beam collimation, the lens array can also be used as a beam splitter in the experiment. To this end, we shift the lens array along the x direction. Figure 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 intensities as shown in Fig. 2(b). The angle between two lobes is about 14°. The light intensity in the rest lobes of Fig. 12 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 present experimental design has a number of advantages compared to previous experiments[10-16] using external cavity designs. First, by using a lens array to split the laser output beam, no beam splitter is needed in the external cavity and loss of the reflection beam power can be avoided. Second, the feedback strength can be easily controlled in a large range through a continuous adjustment of the ratio between two lobes of the array output beam.

The first part of the array output beam is fed back 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 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 frequency locking performance.

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

3 Experimental Results

3.1 Synchronized laser array output

Far-field distribution provides an indication about the degree of synchronization of lasers in the array. In an ideal case, when all the lasers are in a single mode (both transverse and longitudinal) and in-phase, all the laser array power can be collected in a narrow central lobe while for a nonsynchronized array the far field distribution is very broad. The two profiles plotted in Fig. 3 correspond to the far-field light intensity distributions at the free-running state and with the external cavity, respectively. The light output from the laser array is focused with a pair of cylindrical lenses at location ‘B’ in Fig. 1. When the laser array is coupled to the external cavity, the far-field beam profile shows much narrower center lobe with the beam divergence angle of the center lobe being about 0.6°, which is close to the angle of the diffraction limited beam from a single emitter without the external cavity. The peak position (i.e., the emission angle) can be controlled by adjusting the grating angle. We found that the external optical feedback effect was maximized when the reflection beam passes the edge of the laser emission aperture. The M^2 value of the array output beam is evaluated to be approximately 20. Compared to the free-running state, the spatial coherence is improved about 7 times due to the optical feedback from the common external reflector. Spatial coherence can be further enhanced with the reduction of low ‘smile’ and AR-coating ratio of the laser array[18]. It can also be improved by optimizing the collimation optics. One method is to employ two microlens arrays in the collimation optics so that the first lens array increases the filled aperture of each laser and the second array manipulates the beam.

The optical spectrum of the entire laser array output is also measured. Figure 4 plots both the free-running state optical spectrum and a locked spectrum. Clearly, the central lobe of the entire laser array output exhibits a single longitudinal mode. We further verified that the wavelength could be continuously tuned over 802 nm to 814 nm by rotating the grating. During the wavelength, the side mode suppression ratio is larger than 25 dB.

Optical spectrum of individual laser emitters has also been measured. In the free-running state, each laser is lasing at a different center wavelength with a bandwidth of about 1 nm. While with the external optical feedback, all lasers are locked to a single longitudinal mode with a linewidth as small as 0.1 nm.[17] However, each locked wavelengths is slightly different. We have conducted a series of experiments on wavelength locking at different conditions and found that lasers at the end of the array always show different locking wavelengths from the center part.

3.2 Laser Coupling Investigation

The effect of the coupling on the laser array synchronization is a very interesting and challenging issue. In our array, the separation between each emitter is very large (500 μm) compared to the wavelength (808nm), indicating that there is no evanescent coupling in the array. The coupling is achieved due to the external cavity and the nature of this coupling is not trivial. We first investigate the coupling contribution between lasers by studying the RF spectrum and time series. Figure 4 shows a series of RF spectra of individual lasers. The major peak distribution shows a clear beat frequency of about 130 MHz. Since the distance from the laser array to the grating is 60 cm, which corresponds to an external cavity frequency of 4 ns, the beat frequency suggests that the major part of the light coming out from one emitter goes first to its corresponding laser and then feedbacks to itself. In our scheme, the most significant coupling occurs between two laser emitters symmetric to the center. The center emitter is different since it emits to itself as shown by the half period in its RF spectrum.

It is interesting to study the temporal behavior of each laser emitter when the laser array is synchronized. Figure 5 plots a set of time series for a few pairs of laser emitters, LD pair #4 and #16 and LD pair #9 and #11. Here again the coupling structure is verified from the correlation of the time series between two lasers. Each of these pairs shows similar oscillation pattern, although such oscillation patterns vary for different pairs of emitters.

We believe that the mutual coupling between laser emitters at opposite sites of the array center is not the only coupling source. Indeed, both RF spectrum and time series show that these pair-coupled lasers do not exhibit identical spectral or temporal waveforms. In fact, optical feedback induces interactions among different laser emitters. Especially the broadening of each laser emitter in the slow-axis direction will induce certain interactions among near neighborhood lasers. The diffuse focus established by the slow-axis cylindrical lens also ensures crosstalk between submodes and between laser emitters so that the laser resonance modes lock onto each other[19]. We conducted an experiment to verify the influence of the strength of 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 location ‘C’ of Fig. 1) to change the feedback amount. A typical result is summarized in Fig. 7. The five graphs plot the optical spectrum of laser emitter #3 at different edge positions: fully opened state, 75%, 50%, 25%, and fully closed state, respectively. The results show that 50% of the feedback is required in order to achieve the wavelength locking. Another indication from Fig. 7 is that the amount of feedback strength affects the locking wavelength. We believe that this effect is related to the wavelength shift observed in our experiments since lasers at the end side of the array receive less contribution from their neighborhoods.[17]

4. Conclusion

Frequency locking and beam combination of a 19-broad-area semiconductor laser array have been demonstrated using an external cavity configuration that consists of array collimation, projection lenses, and diffraction grating. All 19 lasers are frequency-locked to the single mode with a narrow spectrum bandwidth. The entire array output shows a single transverse mode with the far-field angle closed to the diffraction limited angle of a single broad-area emitter without an external cavity. Based on the measurement of RF spectrum and temporal dynamics of individual laser emitters, we identified the laser coupling configuration in the current experimental design. Such coupling was shown to affect the frequency locking performance of the laser array.

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Figure Captions

Figure1 Schematic of external-cavity experimental setup. Both top view and side view of the setup are shown. 'A': image plane of laser array, 'B': focal plane of laser array, 'C': edge for feedback level adjustment, CL: cylindrical lens. Inset box: beam splitting with lens array.

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) the position of lens array is shifted 250 μm (half of the laser spacing) from (a).

Figure 3 Combined far-field beam profile of the entire laser array measured at 'B' at a drive current of 19 A.

Figure 4 Optical spectra of 19 emitters in free-running state (dashed line) and with external cavity (solid line). The drive current is 19 A.

Figure 5 Measured RF spectrum of five laser emitters with external optical feedback. The external cavity length is ~60 cm.

Figure 6 Measured temporal waveforms of two laser emitter pairs: (a) LD #4 and LD #16, (b) LD #9 and LD #11.

Figure 7 Optical spectrum of the laser emitter #3 at different edge positions of 'C' in Fig. 1. The drive current is 19 A.