Synchronization of Arrays of High Power Lasers

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Semiconductor lasers offer significant operational advantages due to their high efficiency, compactness, and flexibility of pulse repetition rates. Their major drawback - which limits quite severely the scope of their applicability - is the relatively low emission power put out by a single semiconductor laser. To overcome this drawback, we propose a compact, high-efficiency, high-power light source based on a synchronized broad-area laser array.

A variety of techniques have been proposed to synchronize laser arrays and coherently combine beams from separate lasers [1-10]. They involve primarily optical engineering efforts such as MOPA injection locking, evanescent coupling, the use of Talbot cavities, and spectral beam combining. In some instances, optical engineering techniques have indeed produced phase locking in arrays of lasers (mostly, using low-to-moderate power lasers). However, these techniques are not easily scalable. The fundamental difficulty in realizing a scalable design is the complexity of the underlying dynamics. Indeed, lasers are inherently highly nonlinear systems that are capable of producing varieties of complex behaviors that depend quite sensitively on parameter values and initial conditions. One possible consequence of nonlinearity in lasers is that synchronization techniques that are suitable for low power, single mode lasers may not be applicable to high power, single or multimode lasers, because of the possibility of chaotic behavior that high power lasers usually display. Therefore, thorough understanding of this complex behavior is essential for the design of stable, scalable, and robust high power sources.

We designed a novel scalable setup and technique to synchronize high power both CW and pulsed semiconductor laser arrays. Our design combines the major important features necessary to synchronize a nonlinear, possibly chaotic, dynamical system, namely: (a) injection locking and/or reflection from the gratings as a mechanism of mode locking and (b) laser coupling to induce the collective dynamics in the array. We have experimentally demonstrated several designs of synchronization broad-area semiconductor laser arrays using commercially available high-power laser arrays. The key advances of our synchronization experiments include:

(a) One watt of CW power at single transverse and longitudinal mode emission from a single broad area semiconductor laser of an array [12];
(b) Simultaneous synchronization of two individual lasers of a broad-area laser array by external optical injection [9];
(c) Synchronization and coherent beam combination of four separate broad area lasers operating in CW mode with an external reflector; and
(d) Synchronization and coherent beam combination of a 19-laser array operating in CW mode using an external reflector.

The laser array used in the experiments is schematically shown in Fig. 1. The broad-area laser is chosen from a Coherent B1-20C laser diode array. The 125 μm×1 μm aperture of each broad-area laser emits a far-field pattern subtended by 6°×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 each laser is selected by a thin slit. The spectrum of each broad-area laser is measured with an optical spectral analyzer and a Fabry-Perot super cavity.

The single-mode master laser used in this experiment is a 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.

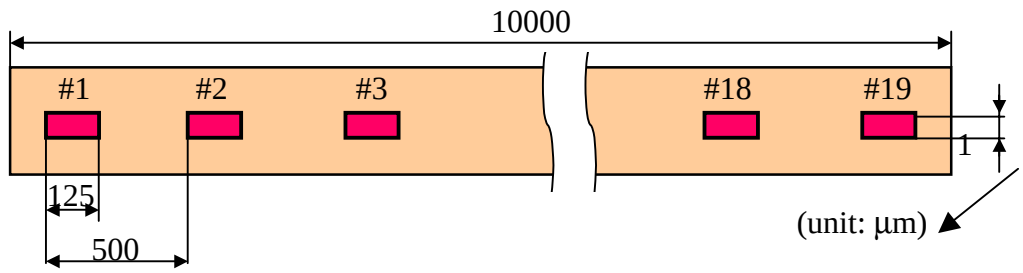

Figure 1: Schematic diagram of the laser array used in our experiments.

We first verified the single longitudinal and single transverse mode behavior in a single broad area laser. The far field pattern is shown in the Figure 2, where the blue line shows the far field pattern of the free running laser, while the red line shows the same for the injection locked one.

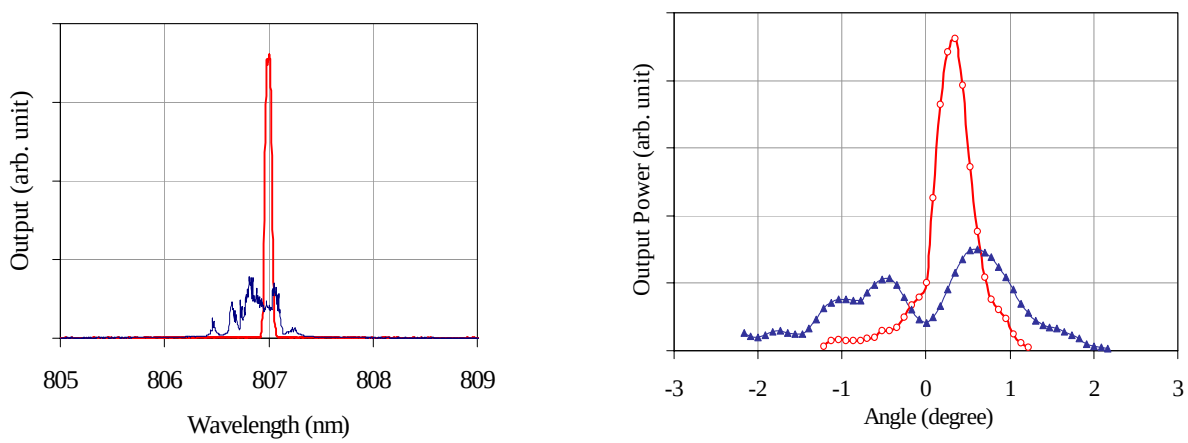

Figure 2: On the left, we show the optical spectrum of free-running (blue line) and injection locked (red line) broad area laser. On the right, we show the far field of the free running laser (blue line) and of the injection locked laser (red line).

Our next figure illustrates the successful synchronization of four separate coupled broad area lasers. The coupling is realized by mutual optical injection among of all four lasers. In addition, we use external reflector (grating) that reflects a portion of light to each of the lasers. To emphasize the role of the coupling, we show in Fig. 3 (left side) the optical spectra of all four uncoupled lasers.

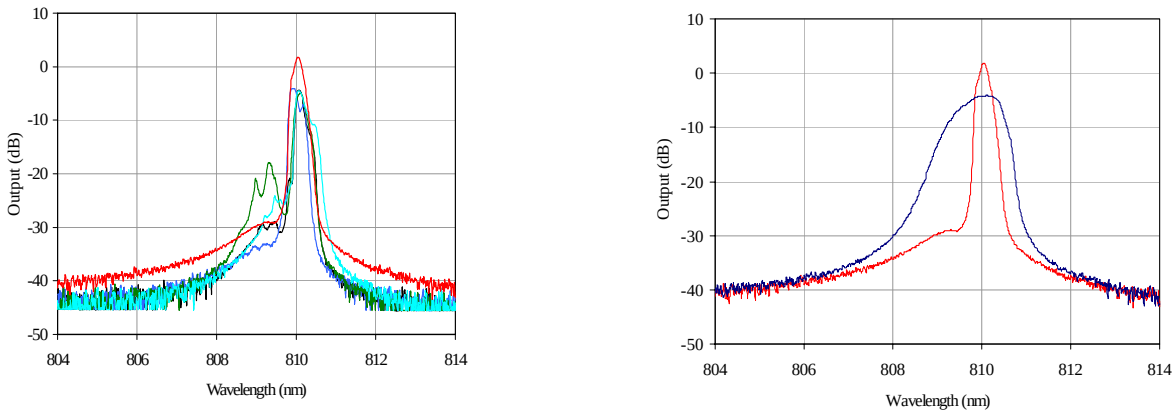

Figure 3. On the left, we show the optical spectra of four separate lasers with no coupling and external reflector. The red line shows the combined spectrum of all four lasers, while the green, blue, purple, and black lines show the optical spectrum of each separate laser. On the right, we show the optical spectrum of all four coupled lasers. The red line shows the spectrum of injection locked lasers, while the blue line shows that of free running lasers.

Figure 3 (right side) shows the spectrum of four separate coupled lasers. One clearly realizes the significant improvement in the spectrum bandwidth.

We next show the far field pattern resulting from the synchronized array of 19 high power broad area lasers. Here we used external reflection to achieve synchronization. Additional work to explore the effects of the coupling on synchronization is in the progress.

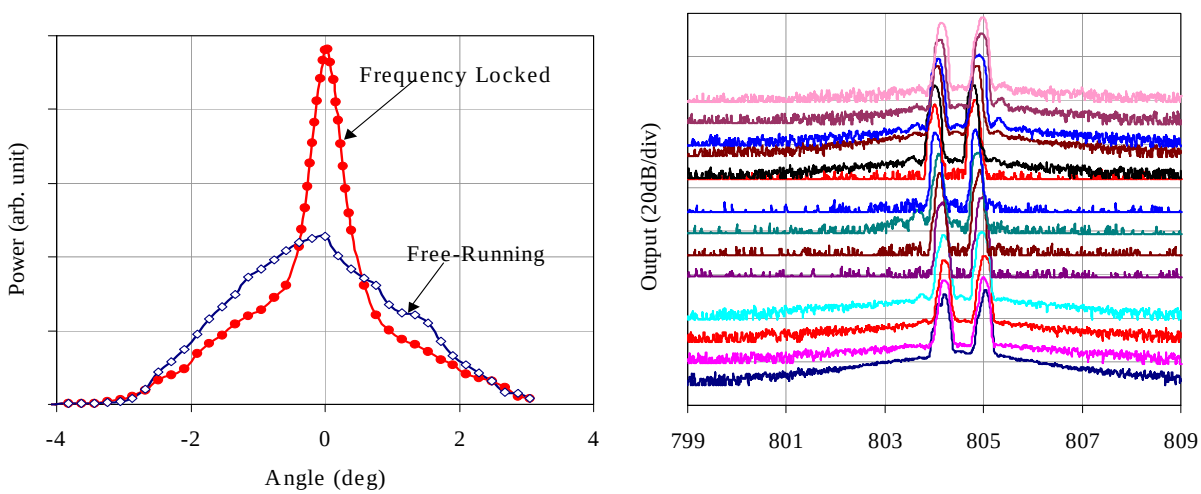

Figure 4: On the left, we illustrate the combined optical spectra of the array of 19 lasers. The red line shows the far-field distribution of the injection locked array, while the blue line shows that of the free-running array. On the right, we demonstrate the optical spectra of 14 (from 19) lasers in the injection locked regime.

To achieve robust synchronization of the laser array, we need to determine best estimates for the underlying operating parameters and assess their associated uncertainties. This can be achieved by using concepts and tools from *sensitivity and uncertainty analysis* (S&UA) [13]. Given the nonlinear equations that specify the array dynamics, sensitivities (defined as the derivatives of the system responses with respect to parameters and inputs) can be calculated to determine and rank the importance of all model parameters and input data to computed quantities

of interest, usually referred to as *system responses*. CESAR is currently developing efficient methods [14] and tools for automated differentiation that accurately compute these sensitivities by direct differentiation of the formal code statements in the numerical simulation of the dynamics. The procedure generates a new, *enhanced* code that not only carries out the standard numerical simulation of the underlying dynamics, but also simultaneously computes *all* the sensitivities in the same run. Moreover, it yields considerably more accurate results than what could be obtained if finite difference techniques were to be used.

Uncertainty analysis methods use these sensitivities to: (*i*) propagate uncertainties from model inputs to outputs, and (*ii*) determine the best estimates for the parameters and their associated (reduced) uncertainties. S&UA guarantees that no *important effects* are overlooked, full nonlinear, time dependent effects are accounted for, and efficient computation of the sensitivities and on-line parameter updating are carried out.

In summary, we demonstrated synchronization of 19 high power broad area semiconductor lasers. Additional work towards improving the coherence of the output beam as well as synchronization of high power pulsed laser arrays is in progress. This research was supported by the Office of Science of the U.S. Department of Energy, under the Basic Energy Sciences Program and by the Office of Naval Research. The Oak Ridge National Laboratory is managed for the U.S. DOE by UT-Battelle, LLC, under contract No. DE-AC05-00OR22725.

References

1. L. Goldberg, H. F. Taylor, J. F. Weller, and D. R. Scifres, “Injection locking of coupled-strip diode laser arrays”, *Appl Phys Lett*, **46**, 236-238 (1985).
2. M. Chun, L. Goldberg, and J. Weller, “Injection-beam parameter optimization of an injection-locked diode-laser array”, *Opt. Let.*, **14**, 272-274 (1989).
3. H. Tsushida, “Tunable, narrow-linewidth output from an injection-locked high-power AlGaAs laser diode array”, *Opt. Lett.*, **19**, 1741-1743 (1994).
4. S. MacCormack, J. Feinberg, and M. H. Garrett, “Injection locking a laser-diode array with a phase-conjugate beam,” *Opt. Lett*. **19**, pp. 120-122, 1994.
5. Y. Braiman, T. A. B. Kennedy, K. Wiesenfeld, and A. Khibnik, “Entrainment of solid-state laser arrays,” *Phys. Rev. A* **52**, pp. 1500-1506, 1995.
6. L. Bartelt-Berger, U. Brauch, A. Giesen, H. Huegel, and Hans Opower, “Power-scalable system of phase-locked single-mode diode lasers,” *Appl. Opt*. **38**, pp.5752-5760, 1999.
7. V. Daneu, A. Sanchez, T.Y. Fan, H.K. Choi, G.W. Turner, and C.C. Cook, “Spectral beam combining of a broad-stripe diode laser array in an external cavity,” *Opt. Lett*. **25**, pp.405-407, 2000.
8. B. Chann, I. Nelson, and T. G. Walker, “Frequency-narrowed external-cavity diode-laser-array bar,” *Opt. Lett*. **25**, pp.1352-1354, 2000.
9. P. Cheo, A. Liu, and G. King, “A High-Brightness Laser Beam From a Phase-Locked Multicore Yb-Doped Fiber Laser Array,” *IEEE Photonics Lett*., **13**, pp.1041 (2001).
10. Y. Liu, H. K. Liu, and Y. Braiman, “Simultaneous injection locking of couples of high power broad-area lasers driven by a common current source”, *Appl. Opt.*, **41**, 5036 (2002).
11. E. J. Bochove, “Theory of Spectral Beam Combining of Fiber Lasers”, IEEE *J Quant Electronics* **38**, 432 (2002).
12. Y. Liu, H. K. Liu, and Y. Braiman, “Injection locking of individual broad area lasers in an integrated high power diode array”, *Appl. Phys. Lett.*, **81**, 978 (2002).
13. J. Barhen *et al*, “Uncertainty analysis of time dependent nonlinear systems”, *Nucl Sci Eng*, **81**, 23-44 (1982).
14. J. Barhen, N. Toomarian, and S. Gulati, “Applications of Adjoint Operators to Neural Networks", *Appl Math Lett*, **3**(3), 13-18 (1990).