Simultaneous Injection Locking of Couples of High Power Broad-Area Lasers Driven by a Common Current Source

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Abstract

We experimentally demonstrate the simultaneous injection locking of pairs of high power broad-area laser diodes in a 19-laser array driven by a common current source. Each pair is injection locked using a single-mode low power semiconductor laser. The frequency and phase locking are verified by the optical spectrum and the interference pattern between the injection-locked lasers. We validate a necessary condition for the injection locking of a broad-area laser array.

Recent advances in the technology of fabricating high-power laser diode arrays have produced CW output power on the order of 100 W from broad-area lasers/laser arrays[1,2]. These lasers are primarily designed for pumping applications and normally have multiple longitudinal modes and poor beam quality. To overcome this drawback, optical injection [3-10] and external cavity [11-13] locking techniques have been proposed. Achieving high power, high quality emission is a crucial requirement for applications such as free-space communications, material and information processing, and directed energy. Injection locking of multiple stripe single-mode laser diode array with an overall array aperture of 100 μm $\times$1 μm and a total output power of less than 1.2W has been reported in the literature [3-6]. 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 also been demonstrated [7-9].

Theoretical and numerical work [14-16] revealed that coherent coupling of a phase-locked laser array results in a very high light intensity which is proportional to the square of the number of the lasers in the array. However, synchronizing a high-power laser array is a very challenging experiment. Laser array is a highly nonlinear system and possesses a variety of complex behavior. One needs to cope with both optical engineering and nonlinear dynamics issues at the same time. In addition, fabrication of lasers arrays is not a perfect process and commercially available laser arrays usually show inhomogeneity in the spectrum. This makes it extremely important to access and control each laser separately. Indeed, in our research we

clearly demonstrate benefits and challenges of such an approach. Our experimental design makes it possible to address each laser separately, thereby to control the injection into each laser cavity. As a consequence, we have obtained simultaneous injection locking with constant phase relationship for different pairs of broad-area laser diodes.

The laser array used in this experiment has 19 InGaAsP broad-area laser diodes with total output power over 20 W. Each broad-area laser in the array has a cavity length of 1 mm and an emitting aperture of 150 $\mu m \times 1\ \mu m$ 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. It is important to note that each broad-area laser in this array has an emitting aperture wider than that of the overall aperture (100 μm) of the laser arrays reported in previous work [3-6]. The single-mode master laser used in this experiment is a laser diode (TOPTICA DL-100) with a linewidth of a few MHz and 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 the 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.

Since the separation between adjacent lasers in the array is much larger than the emitting width of each laser, we need to direct the injection beam into each laser separately to achieve an efficient injection. As a first step, we split the injection light into two parallel beams

with two sets of mirrors and beam-splitters as shown in Fig. 1. By shifting BS1 and M2 with translation stages, one can selectively direct the injection beams into any selected pair of lasers in the array. The beam splitting is realized by a pair of mirror and beam-splitter (BS) which are low-cost and can be easily implemented in a compact size using micro-optics components. All injection beams are controlled by the lens L0 (along *x* direction, see inset in Fig. 1) and the lens L1 (along *y* direction). The proposed beam-splitting scheme can be easily scaled to the injection for more lasers by including the corresponding pairs of mirror and BSs (it is important to note there is no need to use individual collimation lens for each injection beam separately). The spot size of both injection beams in front of the laser array is estimated to be about 100×10 μm. The light output of the laser array passes through the collimation lenses L1 and L2 and is selected by a thin slit. The spectrum of each broad-area laser is measured with an optical spectral analyzer (Agilent 86140B). The phase relationship between two lasers is measured with a Michelson interferometric setup.

We start from the experiment of optical injection to each of 19 lasers. The longitudinal modes of the 19 lasers are different from one another and are in the interval between 806 nm and 810 nm. We observe that the injection locking is obtained only when the frequency of the injection light matches one of the longitudinal modes of the slave laser. We have successfully injection-locked all 19 lasers individually by appropriately matching the frequency between the slave and the master lasers via the drive current. We find that an injection power of only 0.5

mW is required to injection lock a broad area laser with output power of 1W.

Our presumption is that, having enough injection power and homogeneity (in the spectrum) of all lasers in the array, our approach would lead to the synchronization of all (or most) lasers in the array. In the following experiments, we show that, by separately accessing individual laser in the array, a stable simultaneous injection locking can be achieved for different pairs of broad-area lasers whose free-running state longitudinal modes are close to each other. In order to achieve a more efficient injection performance, we first look for pairs of lasers whose longitudinal modes in the free-running state are close to each other. Then we set the injection light frequency to be close to a certain main longitudinal mode in the two slave lasers. The fine tuning of the frequency matching between the slave laser and the injection light is accomplished by carefully adjusting the drive current of the slave laser array. In this way, we are successful in the simultaneous injection locking of several pairs of lasers in the array. These include LD#3 and LD#4, LD#4 and LD#7, LD#12 and LD#14, and LD#14 and LD#15 in the 19-laser array. Representing the results, the simultaneous injection locking of LD#4 and LD#7 is shown in Fig. 2. Here, the injection light wavelength is 808.15 nm and the drive current of the laser array is 10.0 A. One finds that both lasers are simultaneously locked to the same injection frequency. It is noted that there is no significant change in the light output power of the slave lasers with or without the injection locking.

In order to verify the constant phase relationship between the locked lasers, we

measured the interference between the two injected laser outputs with a Michelson interferometric setup. Figure 3 shows an example of the interference pattern between LD#4 and LD#7. A clear interference pattern is obtained when the two lasers are injection locked. The results demonstrate (1) a constant phase difference between the injection-locked lasers and (2) the stability of injection locking of both longitudinal modes and transverse modes. We have also investigated the influence of the reflection of the injection light from the facet of the laser array on the interference pattern. We find that a 3% change of the drive current of the slave laser from its optimum value will completely destroy the interference pattern. This fact clearly indicates that the observed interference pattern is only due to the light outputs of the injection-locked broad-area lasers.

We have measured the stable locking range at different drive current levels. When the drive current is low ($I_d<2I_{th}$), the frequency range for stable locking is linearly dependent on the injection strength (defined as the square root of the injection power). At high drive currents, the locking range shrinks due to the decrease of the ratio between the injection power and the slave laser output power [17,18]. The results suggest that frequency matching is essential in order to achieve injection locking with a moderate injection power. Since the laser array is driven by a common current source and the inhomogeneity is relatively large, we find it challenging to achieve frequency match between the injection light and all slave lasers in the array at the same time. A better quality (more homogeneous array) would require much less injection power.

Alternatively, one may consider using an array where each individual laser diode can be driven separately. It is expected that simultaneous injection locking of multiple lasers can be achieved when the frequency of each laser is separately controlled.

In conclusion, we have experimentally demonstrated simultaneous injection locking of pairs of broad-area lasers in an integrated 19-laser array driven by a common current source. The stable phase relationship between the locked lasers are verified through their interference pattern. We have observed that a critical condition required for the injection locking of broad-area lasers in a large array is the frequency matching between the master and slave lasers. If the mode of each slave laser in the array is matched to that of the master laser, simultaneous locking of all the lasers in the array may be realized based on our injection scheme with a low injection power. Considering the large power and compact configuration of the broad-area array employed, an ultra-high power density can be realized by appropriately coupling the output beams from different broad-area laser diodes locked by the same injection laser.

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References

[1] D. Botez and D. R. Scifres, Diode Laser Arrays, Cambridge University Press, (1994).

[2] N. W. Carlson, Monolitic Diode-Laser Arrays, Springer-Verlag (1994).

[3] L. Goldberg, H.F. Taylor, and J.F. Weller, Appl. Phys. Lett. **46**, 236 (1985).

[4] M. K. Chun, L. Goldberg, and J. F. Weller, Opt. Lett. **14**, 272 (1989).

[5] H. Tsuchida, Opt. Lett. **19**, 1741 (1994).

[6] S. MacCormack, J. Feinberg, and M. H. Garrett, Opt. Lett. **19**, 120 (1994).

[7] G. L. Abbas, S. Yang, V. W. S. Chan, and J. G. Fujimoto, Opt. Lett. **12**, 605 (1987).

[8] H. Horiuchi, T. Shimura, T. Omatsu, O. Matoba, and K. Kuroda, Appl. Phys. B **68**, 1021 (1999).

[9] T. Pawletko, M. Houssin, M. Knoop, M. Vedel, and F. Vedel, Optics Commun. **174**, 223 (2000).

[10] L. Bartelt-Berger, U. Brauch, A. Giesen, H. Huegel, and Hans Opower, Appl. Opt. **38**, 5752 (1999).

[11] V. V. Apollonov, S. I. Derzhavin, V. V. Kuzminov, D. A. Mashkovskii, A. M. Prokhorov, V. N. Timoshkin, and V. A. Filonenko, Quantum Electronics **29**, 839 (1999).

[12] V. Daneu, A. Sanchez, T.Y. Fan, H.K. Choi, G.W. Turner, and C.C. Cook, Opt. Lett. **25**, 405 (2000).

[13] B. Chann, I. Nelson, and T. G. Walker, Opt. Lett. **25**, 1352 (2000).

[14] M. Silber, L. Fabiny, and K. Wiesenfeld, J. Opt. Soc. Am. B **10**, 1121 (1993).

[15] Y. Braiman, T. A. B. Kennedy, K. Wiesenfeld, and A. Khibnik, Phys. Rev. A **52**, 1500 (1995).

[16] P. K. Jacobsen, R. A. Indik, J. V. Moloney, A. C. Newell, H. G. Winful, and L. Raman, J. Opt. Soc. Am. B **8**, 1674 (1991).

[17] J. M. Liu and T. B. Simpson, IEEE J. Quantum Electron. **30**, 957 (1994).

[18] D. J. Gallant, Appl. Phys. Lett. **76**, 3364 (2000).

Figure 1

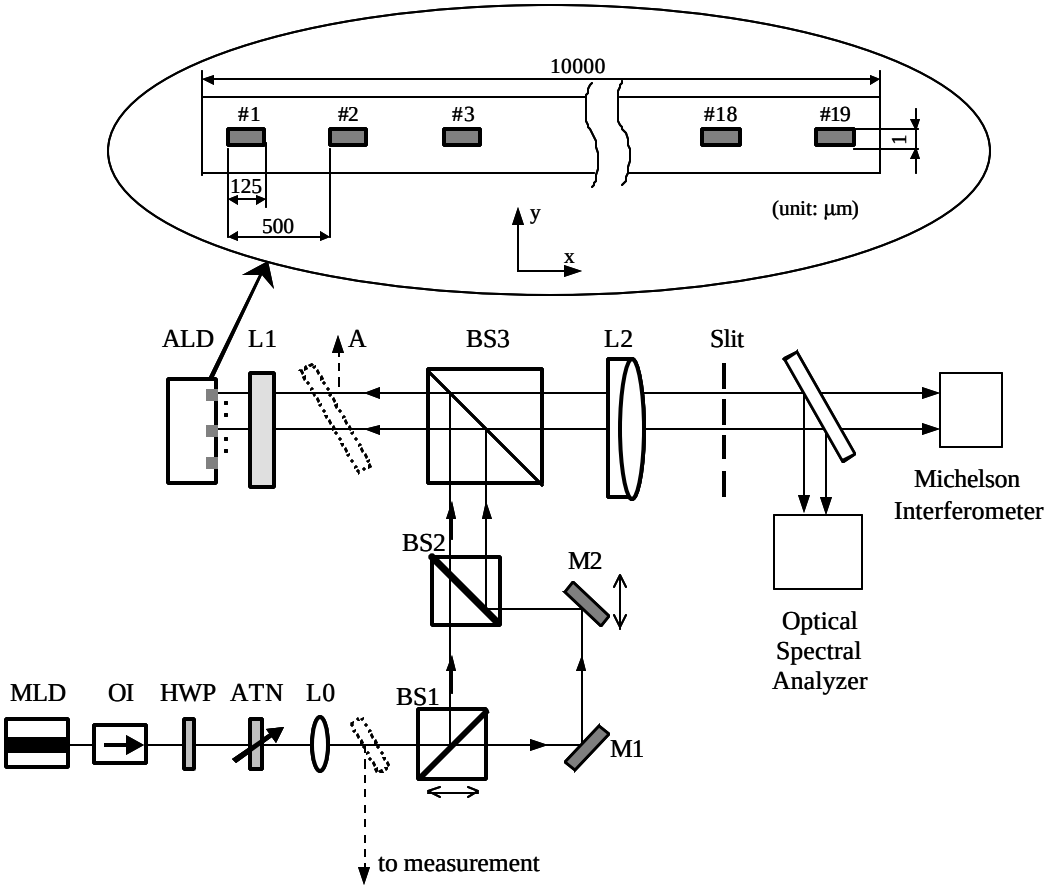

Fig. 1 Schematic experimental setup: ALD: array laser diode, MLD: master laser diode, L0: injection beam collimation lens, L1: fast-axis cylindrical lens, L2: slow-axis cylindrical lens, OI: optical isolator, HWP: half-wave plate, ATN: attenuator, BS: beam splitter, M: mirror. Inset: configuration of 19-laser array.

Figure 2

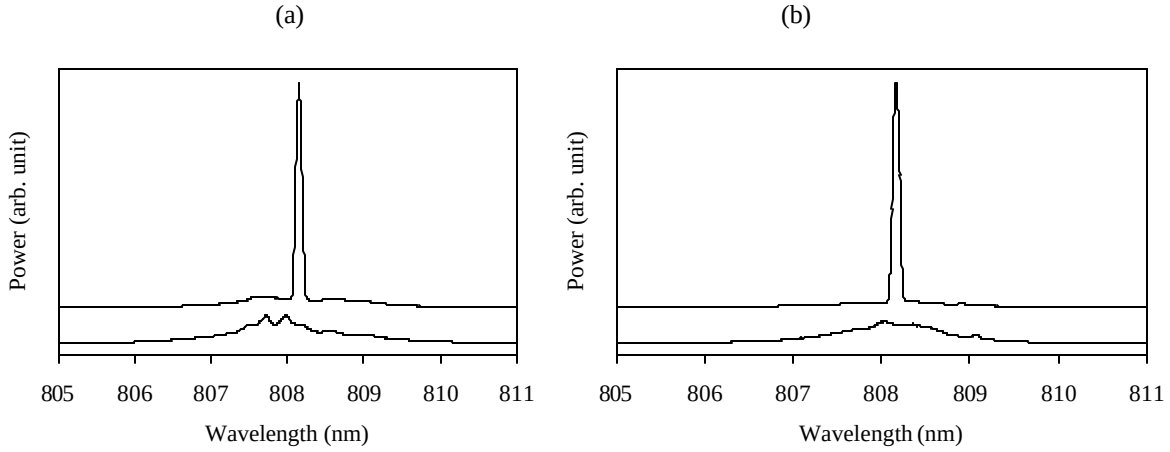

Fig. 2 Optical spectrum of (a) LD#4 and (b) LD#7 before (lower trace) and after (upper trace) the injection locking. The spectrum after the injection locking is vertically shifted for better exhibition. The lower and upper traces are plot with the same scale.

Figure 3

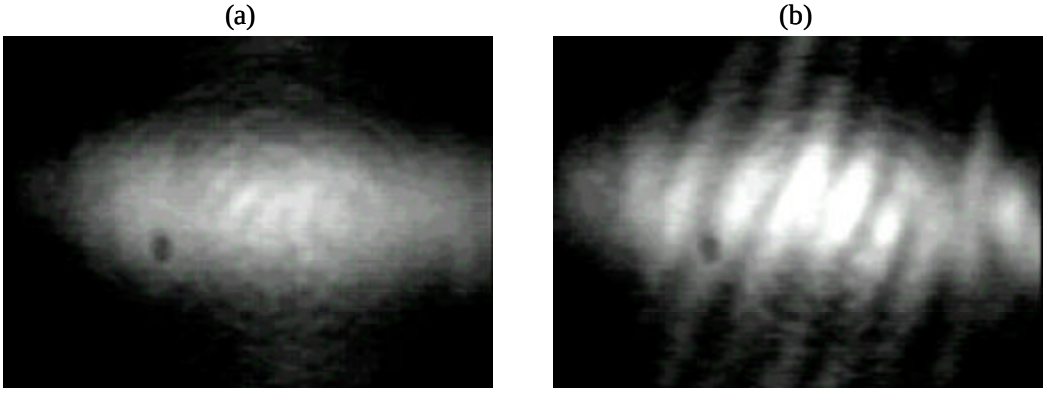

Fig. 3 Interference pattern between light outputs of LD#4 and LD#7. (a) Before injection-locking and (b) after injection-locking.