# Coupling of diode laser arrays with photorefractive passive phase conjugate mirrors

Mordechai Segev, Shimon Weiss, and Baruch Fischer
*Department of Electrical Engineering, Technion—Israel Institute of Technology, Haifa 32000, Israel*

(Received 5 January 1987; accepted for publication 24 March 1987)

An experimental study of the coupling of diode laser arrays to various photorefractive phase conjugate mirrors is presented. We demonstrate frequency locking of arrays as well as the control of their emitted light patterns.

Phase-locked laser diode arrays (LDA's) are the focus of intensive research, due to their small size and relatively high power capabilities.[1,2] For many applications, however, the requirements of high coherence and single lobed beams have not been met satisfactorily. Several approaches have been taken to realize these goals. Chirping the gain profile across the device,[3–7] injection locking,[8,9] and coupling to external cavities with a spatial filter or grating[10–12] are some of these techniques. A theoretical analysis of an LDA coupled to an external cavity is presented in Ref. 13.

In this letter, we demonstrate the coupling of LDA's to various photorefractive passive phase conjugate mirrors (PPCM's). We present experimental results of locking two LDA's, and show ways of controlling the light field and frequency spectrum of an array.

The use of photorefractive oscillators and PPCM's, instead of a regular mirror, to form the coupling unit and the external cavity, allows ease of alignment and better selectivity of the LDA's spectrum (due to Bragg selectivity of the gratings written in the crystal). Moreover, the photorefractive oscillation, which is a common light (photons) "reservoir" of all the emitters, provides a special coupling mechanism.

The PPCM's used were the double phase conjugate mirror (DPCM), the semilinear PPCM, and the ring PPCM.[14,15] In one experiment two LDA's were mutually injection locked by the DPCM in a manner similar to that of our recent work with argon ion lasers.[16] In the present work, besides the locking of the arrays, we also controlled the output field of the LDA by introducing a spatial filter inside the external cavity. Frequency shifts were obtained with the ring PPCM by slightly changing the mixing configuration. In other recent works, phase conjugation techniques were employed to couple single lasers. Two single diode lasers were coupled via the ring PPCM[17] and two argon ion lasers with the "cat" mirror.[18] In another work, Nd:YAG amplifiers were coupled by stimulated Brillouin scattering (SBS).[19]

The arrays used here were commercial, ten-element, gain-guided devices (Spectra Diode Labs, model SDL-2410-C) without antireflection coatings operating near 800 nm. Typical threshold currents of the arrays were about 200 mA and the output powers for driving currents of 300 mA were about 100 mW (cw operation). Under regular conditions, both arrays lased in the preferential highest supermode (antiphase between neighboring emitters) with a twin-lobe far-field pattern.[20]

The setup for the injection locking experiments of two LDA's coupled to the DPCM is shown in Fig. 1. In the DPCM, two input beams, which can originate from different lasers, pump a photorefractive crystal. Two other beams, which are phase conjugates of the pumps, are produced simultaneously by an efficient four wave mixing process. As shown in Fig. 1, light beams from two LDA's were focused onto opposite sides of a $BaTiO_3$ crystal in a DPCM configuration. The crystal was held in a cuvette and immersed in an index matching oil. Its dimensions were $7 \times 6 \times 3$ mm$^3$. The basic experimental configuration was the same as described in Refs. 15 and 16, except for slightly smaller angles between the two input beams. This maintained the same optimal grating period despite the longer light wavelength. Both beams were extraordinarily polarized, and the crystal's $c$ axis was along the $\hat{z}$ direction. The spectrum of the LDA was monitored with a monochromator, using reflections from the cuvette. A beamsplitter, positioned in the left arm between LDA-1 (which will be referred to as the "slave" laser) and the crystal, was used for recording the far-field pattern of the slave LDA (with a scanning slit) as well as the phase conjugation reflectivity. One of the two lobes of LDA-2 (the "master" laser) was blocked. A variable slit (VS) was positioned in the left arm between the beamsplitter and the crystal.

We noticed a considerable increase in the phase conjugation reflectivity when one of the slave's lobes was also blocked. This might be due to the fact that when both lobes are present, the near field of the LDA is imaged into the crystal, thus forming an additional grating which competes for the crystal gain with the self-induced grating (the grating which is responsible for the two laser's beam coupling). This

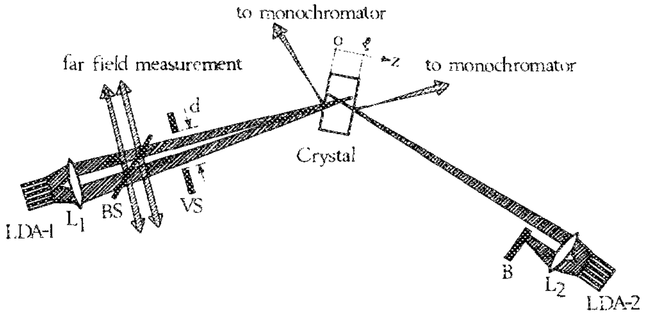

FIG. 1. Schematic of the experimental setup for the injection locking experiments: LDA—laser diode array, *L*—lens, BS—beamsplitter, VS—variable slit, *C*—crystal, *B*—blocking unit.

causes a reduction in the overall diffraction efficiency and the phase conjugation reflectivity.

In the first experiment, we studied the spectrum of LDA-1 under the injection of an external beam originating from LDA-2. Both arrays had one lobe blocked, as explained above. The slave was operated at $1.1I_{\text{th}}$ ($\sim 10$ mW) and the master at $1.3I_{\text{th}}$ ($\sim 50$ mW). ($I_{\text{th}}$ is the threshold current of the free-running array. After locking, it usually decreased to about 90% of its original value.) The intensity of the injected beam at the facet of the slave was 10 mW. The spectra of both arrays, prior to and during locking conditions, are shown in Figs. 2(a) and 2(b), respectively. The slave, operated near its threshold, had only one longitudinal mode. The broadening and the fine splitting structure of this single mode indicates that the array lased with a superposition of several supermodes.[21] The master laser had four narrower longitudinal modes, and seemed to lase with only one dominant supermode (the highest one). During locking, the slave's spectrum was shifted by 12 Å towards the master. The master's spectrum became narrower with only two dominant modes. The slight shift of the oscillation's longitudinal modes is probably due to different internal cavity lengths of the two arrays. This may be eliminated by using an antireflection coated slave laser and single mode master laser.

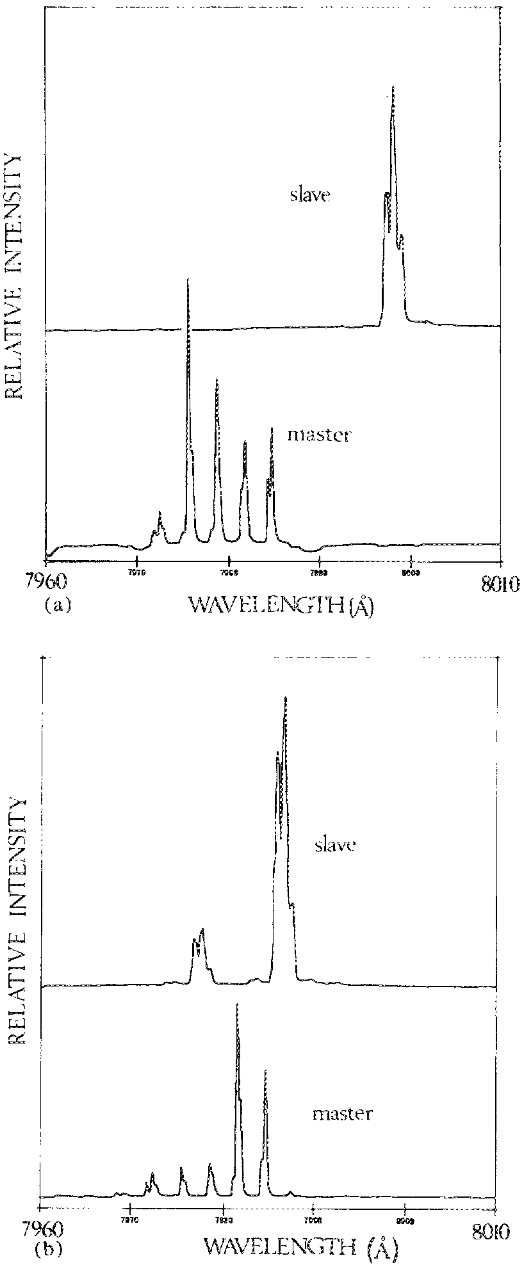

FIG. 2. Spectra of the two LDA's (a) prior to locking and (b) during locking.

A basic advantage of our technique is the complete spatial retrieval of the reflected feedback to the laser array due to the phase conjugation property. This does not prevent the mutual intercoupling of the laser channels of the array. The common PR oscillation of the PPCM provides the needed photon sharing and coupling mechanism.

A similar configuration to Fig. 1 was used to study the far-field pattern of the slave LDA under locking conditions. Here the variable slit (VS) was used to block symmetrical portions of the two lobes of LDA-1, thus introducing losses for the higher supermode.[11] We started the DPCM oscillation with both lobes exposed. The slave operated at $1.05I_{\text{th}}$ ($\sim 10$ mW) and the master at $1.35I_{\text{th}}$ ($\sim 50$ mW). As explained above, the oscillation was not efficient under these circumstances, and the injected power at the slave's facet was less than 1 mW. Gradually narrowing the aperture of the variable slit (decreasing $d$ in the figure) caused an efficient oscillation to build up and an increase in the injected intensity, reaching a point in which the array switched to the single lobed mode of operation. The far-field patterns prior to and during locking are shown in Figs. 3(a) and 3(b) respectively. The typical angle full width half-maximum for the single lobed far-field pattern was 1.5°–3°. This indicates the possible existence of several low-order supermodes.[11] The injected intensity at the facet of LDA-1 increased to 5 mW, due to efficient mixing in the crystal resulted from the disappearance of the parasitic grating. We stress that in contrast to previous reported results,[8,9] the single lobe, under injection locking, was centered around the facet's normal.

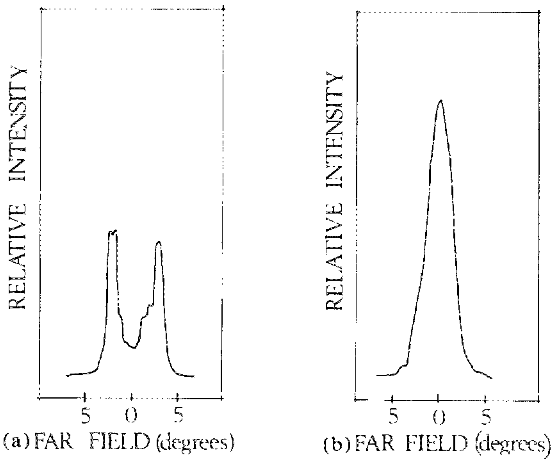

FIG. 3. Far-field pattern of the "slave" LDA for (a) free-running operation and (b) with external feedback from the DPCM filtered by a variable slit.

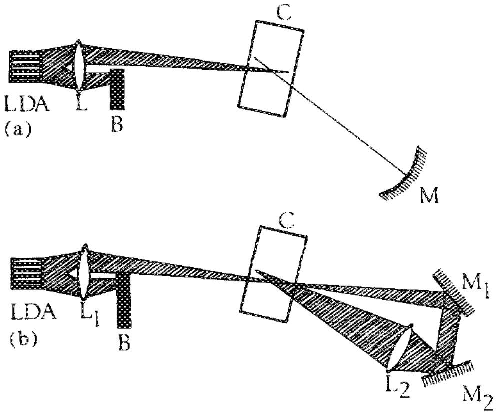

FIG. 4. Schematic of LDA coupled to the (a) semilinear PPCM and (b) ring PPCM (symbols as in Fig. 1).

Another interesting point is that after efficient oscillation buildup, it was possible to remove the variable slit (VS) and still have the single lobed far-field pattern. This is due to the higher gain for that operation mode introduced by the wave mixing in the crystal. Increasing the LDA-1 current sustained the locked position till $1.2I_{\text{th}}$, where the array switched again to a combination of higher supermodes, with a twin lobed far field. This may be due to the increase in evanescent coupling between the emitters, as a result of the higher current, which then dominates with respect to the external coupling. We believe that an LDA with weak coupling between the lasing channels should give even better results.

We also operated the LDA with other self-pumped PCM configurations, the semilinear and ring PPCM's, as shown schematically in Fig. 4. These two configurations are of more reminiscence to an external cavity coupling since both devices are passive in nature. The phase conjugation reflectivities were 5% for the semilinear PPCM and 10% for the ring PPCM. Taking into account the blocking and Fresnel reflections, the ratio of the reflected field to the output intensity of the LDA was less than 3%. For both PPCM's we noticed considerable changes in the far-field pattern as a function of the blocking position, but not a single lobe. We were able to control, however, the LDA spectra by slightly changing the ring configuration. Shifts of 15 Å were observed. This effect has been reported for regular diode lasers.[22] We also achieved switching of the LDA from multilongitudinal mode operation to a single longitudinal mode. These results will be reported elsewhere.

To summarize, we have studied the coupling properties of laser diode arrays to photorefractive PPCM's. We succeeded in locking two different arrays and demonstrated the control of the array's light field structure and spectra. Our results suggest ways to lock several arrays together and to control their far-field patterns.

We wish to thank Zeev Shehory for his technical assistance. This work was partially supported by the National Council of Research of the Ministry of Science in Israel.

[1] D. R. Scifres, C. Lindström, R. D. Burnham, W. Streifer, and T. L. Paoli, Electron. Lett. **19**, 169 (1983).
[2] D. Botez and J. C. Connolly, Appl. Phys. Lett. **43**, 1096 (1983).
[3] E. Kapon, C. Lindsey, J. Katz, S. Margalit, and A. Yariv, Appl. Phys. Lett. **45**, 200 (1984).
[4] D. F. Welch, D. Scifres, P. Cross, H. Kung, W. Streifer, R. D. Burnham, and J. Yaeli, Electron. Lett. **21**, 603 (1985).
[5] C. P. Lindsey, E. Kapon, J. Katz, S. Margalit, and A. Yariv, Appl. Phys. Lett. **45**, 722 (1984).
[6] D. E. Ackley, Electron. Lett. **20**, 695 (1984).
[7] E. Kapon, J. Katz, S. Margalit, and A. Yariv, Appl. Phys. Lett. **45**, 600 (1984).
[8] L. Goldberg, H. F. Taylor, J. F. Weller, and D. R. Scifres, Appl. Phys. Lett. **46**, 236 (1985).
[9] J. P. Hohimer, A. Owyoung, and G. R. Hadley, Appl. Phys. Lett. **47**, 1244 (1985).
[10] J. E. Epler, N. Holonyak, Jr., R. D. Burnham, T. L. Paoli, and W. Streifer, Appl. Phys. Lett. **45**, 406 (1984).
[11] J. Yaeli, W. Streifer, D. R. Scifres, P. S. Cross, R. L. Thornton, and R. D. Burnham, Appl. Phys. Lett. **47**, 89 (1985).
[12] C. C. Hasnain, D. F. Welch, D. R. Scifres, J. R. Whinnery, A. Dienes, and R. D. Burnham, Appl. Phys. Lett. **49**, 614 (1986).
[13] A. Hardy, W. Streifer, and M. Osinski, Appl. Phys. Lett. **49**, 185 (1986).
[14] M. Cronin-Golomb, B. Fischer, J. O. White, and A. Yariv, IEEE J. Quantum Electron. **QE-20**, 12 (1984).
[15] S. Weiss, S. Sternklar, and B. Fischer, Opt. Lett. **12**, 114 (1987).
[16] S. Sternklar, S. Weiss, M. Segev, and B. Fischer, Opt. Lett. **11**, 528 (1986).
[17] M. Cronin-Golomb, A. Yariv, and I. Ury, Appl. Phys. Lett. **48**, 1240 (1986).
[18] J. Feinberg and G. D. Bacher, Appl. Phys. Lett. **48**, 570 (1986).
[19] D. A. Rockwell and C. R. Giuliano, Opt. Lett. **11**, 147 (1986).
[20] D. R. Scifres, W. Streifer, and R. D. Burnham, IEEE J. Quantum Electron. **QE-15**, 917 (1979).
[21] D. R. Scifres, W. Streifer, R. D. Burnham, T. L. Padi, and C. Lindström, Appl. Phys. Lett. **42**, 495 (1983).
[22] M. Cronin-Golomb and A. Yariv, Opt. Lett. **11**, 455 (1986).