International Journal of Nonlinear Optical Physics
Vol. 1, No. 2 (1992) 431–445

PHOTOREFRACTIVE TECHNIQUES FOR DIODE LASER BEAM COMBINATION

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Received 8 May 1991

Techniques for high-power laser array beam combination processes involving photorefractive materials are reviewed. Details of an all semiconductor laser scheme for the amplification and subsequent photorefractive beam clean-up of a diffraction limited single-mode laser output is presented. Powers in excess of 100 mW (>220 mW accounting for Fresnel losses) are obtained in a diffraction limited signal beam, corresponding to an array to diffraction limited beam transfer efficiency of 33%. Details of a reflection geometry phase conjugate master oscillator-power amplifier scheme which offers the possibility of power scaling between a number of high-power semiconductor laser amplifiers are presented. Using this technique, a 13-dB amplification of a diffraction limited signal beam is obtained using a commercially available, 10-stripe gain-guided device with no special coatings.

Semiconductor lasers provide a compact, high-power, high-efficiency source of quasi-monochromatic light and have found many applications as primary sources and optical pumps in solid-state mini- and micro-laser systems. The possibility of obtaining a high-power, diffraction limited output from semiconductor laser devices opens up many further applications, such as efficient second-harmonic generation to more useful shorter wavelengths, nonlinear frequency mixing techniques and pumping of high-power waveguide laser systems. The output from single-stripe, single-longitudinal and transverse-mode diode lasers do not currently exceed the 100-mW level due to catastrophic thermal damage caused by the intense optical field generated at the diode laser facet ($\sim 5\ \mathrm{MW/cm^2}$). Solutions to the problem of obtaining higher powers from diode laser devices have involved the expansion of the active region in the plane parallel to the lasing junction so as to reduce the optical intensity at the laser facet. This process, illustrated in the development of the broad-stripe and diode laser array, has resulted in a dramatic increase in the raw power available from semiconductor laser devices, but has been accompanied by a significant decrease in the spatial and spectral quality of the output obtained. For example, a typical single-stripe, single-mode diode laser can exhibit a brightness which is four orders of magnitude greater than that obtainable from a conventional high-power diode laser array. For many applications, especially those with stringent requirements on maintaining a tight focus or launching into waveguides, this loss of brightness can greatly decrease the effectiveness of these sources.

Current techniques for the spatial and spectral enhancement of high-power diode laser outputs can be placed in two main categories; those involving external cavity feedback [1–3] and those using injection locking processes to extract the available gain from the array into a diffraction limited signal beam.[4–6] Photorefractive materials and their unique abilities, namely low-power self-pumped phase conjugation and efficient two-beam coupling at GaAlAs laser wavelengths, present themselves as ideal media for diode laser array combination and brightness enhancement.

Photorefractive materials have previously been used for many processes for diode laser array brightness enhancement. Firstly, a number of techniques have been developed which utilize the ability of photorefractive materials to efficiently phase conjugate at the wavelengths and power available from diode laser devices. External cavity configurations involving the use of self-pumped phase conjugate mirrors have significant advantages over conventional external cavity configurations because exact retroreflection into the diode resonator is guaranteed by the nature of the phase conjugation process. External cavity phase conjugate resonators have been used to demonstrate impressive linewidth narrowing and frequency scanning when coupled to a single-mode diode laser,[7] and single-lobe emission[8] and mode-locked operation[9] when coupled to a high-power laser array.

Secondly, the photorefractive mutually pumped phase conjugate mirror (MPPCM) has been demonstrated to allow the self-aligned phase locking of two separate diode laser sources, thus overcoming the stringent positioning requirements of conventional injection locking processes.[10–12] In addition, the self-aligning ability of the MPPCM geometry shows great promise for the injection locking of high-power diode laser bars which is currently very technically difficult using conventional injection locking processes. Finally, and of potentially greatest interest, is the use of the two-beam coupling and phase conjugating properties of photorefractive materials to couple the outputs of two or more phase locked lasers in order to obtain a very high power, diffraction-limited output beam.

The Photorefractive Effect

The photorefractive effect[13] results from changes in refractive indices in electro-optic materials based on the spatial modulation of photocurrents by nonuniform illumination. When the nonuniform illumination results from the interference of two coherent recording beams, each recording beam sees the refractive index profile as a transmission diffraction grating. The transmitted fraction of one beam and the diffracted fraction of the other beam are collinear on exiting the crystal and see interference effects, the nature of which, either destructive or constructive, depends on the relative orientation of the crystal c–axis. This results in the steady-state, nonreciprocal transfer of energy from one beam to the other and is the fundamental process behind photorefractive two-beam coupling in suitable materials such as barium titanate and SBN (strontium barium niobate). The two-beam coupling gain G is defined as the ratio of the power in the transmitted signal beam with the pump beam present to the transmitted signal beam power with no pump beam present. The gain for an incident signal beam I_s when an incident pump beam I_p is present is given by

$$G = \frac{(1 + r)\exp(\Gamma\gamma l)}{1 + r\exp(\Gamma\gamma l)}, \tag{1}$$

where r = incident beam intensity ratio (I_s/I_p), γ = mutual coherence parameter, l = effective interaction length in crystal, and Γ = two-wave mixing gain coefficient, which depends on geometry, polarization and material parameters.

In addition, theoretical and experimental evidence[14] has shown that the phase and spatial profile of the signal beam is preserved in the two-beam coupling process, irrespective of any phase aberrations in the pump beam. This is an important consideration when the diffraction limited nature of the output beam is critical.

Unlike most other nonlinear optical processes, the magnitude of the photorefractive effect does not depend upon the intensity of the incident radiation, but instead it depends on the time-integrated energy absorbed from the incident radiation. This is the property which enables photorefractive materials to exhibit large nonlinearities even at the relatively low intensities available from continuous-wave diode laser devices. Much research is currently directed into development of photorefractive materials which exhibit large nonlinearities at the GaAlAs range of wavelengths. Of the photorefractive materials presently available, rare earth doped SBN[15] and barium titanate[16,17] show greatest promise for use at these near infrared wavelengths. In most of the previous photorefractive experiments carried out at diode laser wavelengths, barium titanate has been the preferred material because of its large electro-optic coefficients and its ability to exhibit a strong photorefractive response in the near infrared. Measurement of the two-wave mixing gain coefficient at 830 nm for a nominally undoped $BaTiO_3$ sample[18] gives a maximum value for Γ of 18 cm^{-1}, which is roughly half that observed at 488 nm, but adequate for most of the beam combining processes discussed below.

Beam Combining Techniques

The coherent combination of the outputs from a number of high-power diode laser devices offers the potential of a very high power, diffraction limited output from an all semiconductor system. The thermal inhomogeneity and heat extraction problems encountered in conventional higher-power laser devices are avoided by having the elements of the laser system physically separated and hence much easier to efficiently heatsink. Coherent combination techniques have been able to achieve the higher powers obtainable by conventional array and broad-stripe devices, but with no sacrifice to the diffraction limited nature of the output beam. Unlike almost all other techniques of brightness enhancement of high-power laser arrays which can only generate a diffraction limited output in the far-field, photorefractive beam combining techniques are easily capable of generating circular Gaussian diffraction limited beams which are far more useful for many end applications.

As can be seen from the strong γ dependence in Eq. (1), a necessary criterion for achieving good power transfer efficiencies in two-beam coupling is that the two beams have a time varying relative phase relationship which is much less than the photorefractive response time of the material used. In the case of $BaTiO_3$, at the typical wavelength and intensities available from diode lasers, the response time is approximately 10 seconds at room temperature. With conventional diode laser arrays, where a number of lasing stripes are fabricated in close proximity on a single substrate, phase locking between adjacent stripes is achieved by means of an overlap of the evanescent fields of neighboring waveguides. The lowest threshold array mode, and hence the preferred lasing mode, corresponds to antiphase operation between adjacent stripes, thus minimizing the field generated in the lossy interstripe regions. For suitable geometries (Fig. 1), it is possible to arrange for the output from one array stripe to couple with the rest of the array output leading to a sequential transfer of energy into a diffraction limited output. This technique has been able to achieve a transfer of 48% of the output power of a 100 mW, 10-stripe array into a diffraction limited beam.[19] The application of this technique to higher-power diode laser devices is, however, limited due to the decrease in the relative interstripe coherence that is obtained as the number of lasing stripes is increased. Extension of this technique to high-coherence, index-guided laser arrays or the new generation of surface emitting diode laser geometries may be able to yield much more significant power transfers.

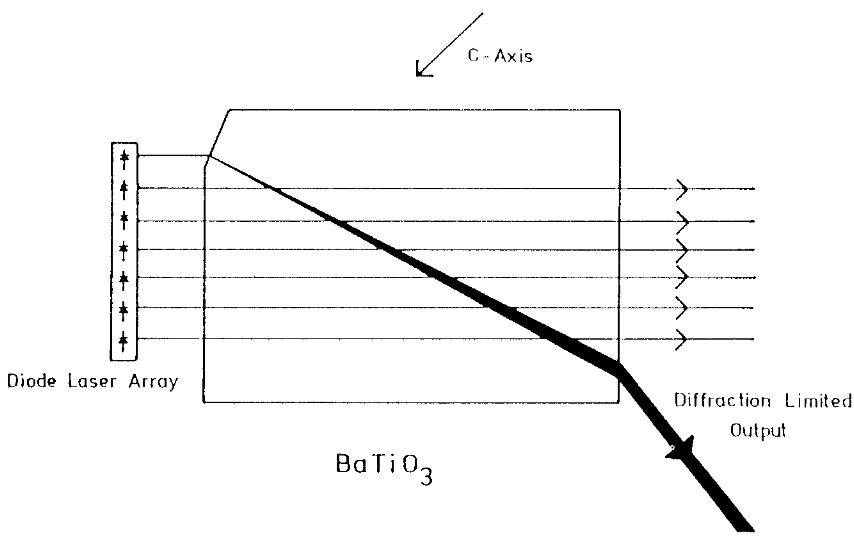

Fig. 1. Schematic for successive transfer of the array output power into one stripe from that diode laser array. The c-axis is oriented at 45° in order to optimize the beam coupling efficiency.

Alternatively, relative phase stability can be achieved between two physically separate laser devices by injection locking[4–6] of a diode laser array (pump) with a fraction of a single-stripe (signal) output beam. Current models[20] suggest that diode laser arrays act as weakly perturbed Fabry–Perot amplifiers under injection locking conditions, the observed injection locking resulting from a multipass amplification of the injected beam which extracts most of the available gain from the laser array. When viewed as such, the injection locking and coherent beam combination of multiple array outputs can be better understood as a process of amplification and subsequent beam clean-up by a diffraction limited, single-mode diode laser output.

Previously, the possibility of injection-locking and combining of two or more single-stripe diode lasers via a binary phase grating has been demonstrated[21] leading to the conversion of multiple outputs into a single-output beam. The use of a dynamic photorefractive grating in place of a fixed grating has advantages in terms of beam self-alignment and improved scalability to multibeam coupling processes. High coupling efficiencies have been obtained by the use of a $BaTiO_3$ crystal in place of the fixed grating, transfer efficiencies of up to 80% having been reported between the outputs from two locked single-stripe diode lasers.[22] These methods demonstrate reasonably high coupling efficiencies, but because of the inherently high losses and low power outputs from single-stripe diodes, only low power beams were obtained, the highest reported output power being 5.8 mW in the amplified beam.[23] Clearly, in order to achieve high powers in the amplified beam it is important to use higher power injection locked lasers in order to obtain the pump powers necessary for large gains for the signal beam. To assess the feasibility of such a scheme for the combination of multiple high-power lasers, it was first necessary to demonstrate the efficient amplification of a diffraction limited diode laser output using a single injection locked laser array pump.[24] In previous work, the degree of success has been assessed in terms of the photorefractive coupling efficiency between the two lasers. For the purposes of our experiment, the absolute power available in the amplified signal beam was of greater concern, so the system was optimized with respect to this parameter as opposed to the coupling efficiency. The work of Verdiell et al.[22] describes a similar system to the one described below which is optimized to obtain a maximum coupling efficiency (53%).

Figure 2 shows the apparatus used for the locking and subsequent coherent combination of the outputs from the single-stripe diode laser and the diode laser array. The single-stripe laser (Sharp LTO 17MD) was stabilized to better than ± 0.1 °C at a temperature of 18.4 °C, and emitted 45.6 mW at a wavelength of 807 nm in a diffraction limited, elliptical beam. The coherence length of the laser was measured to be in excess of 5 m which was perfectly satisfactory for our purposes. The slave laser array was a 1 W, 20-stripe gain-guided device (SDL 2462-P1) operated at a temperature of 14.4 °C in order to achieve a good match between slave and master laser wavelengths. Further tuning of slave laser wavelength was provided by a slight variation in the operating current. A tunable Faraday isolator was used to prevent the output from the slave laser array from

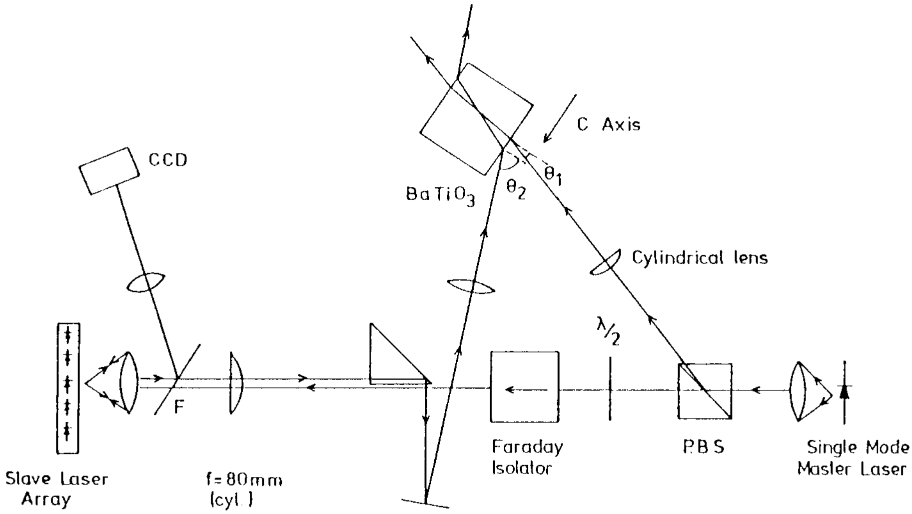

Fig. 2. Experimental setup for injection locking and beam combination. Single-mode master laser output is split at polarizing beam splitter (PBS), one fraction being injected into slave laser array and the other acting as the signal beam. Array far-field pattern is monitored by reflection from optical flat (F) using CCD camera. Pump and signal beam angles at crystal are $\theta_1 = 68°$ (Brewsters angle) and $\theta_2 = 48°$, respectively.

returning back down the injecting path and causing instabilities in the master laser.

The horizontally polarized master laser output was collected with a collimating lens (N.A. = 0.6) and directed toward a polarizing beam splitter, the orientation of which determined the exact beam-splitting ratio. The injecting beam polarization was then rotated through 45° using a quartz half-wave plate and the beam passed through a Faraday isolator which provided a reverse attenuation of 38 dB. Injection beam shaping was provided by means of an $f = 80$ mm cylindrical lens and an $f = 8$ mm collimating lens resulting in a horizontal line focus being injected, at an angle of 10°, into half of the laser array output facet. The far-field pattern of the array was monitored using a CCD camera and a video analyzer. In order to achieve a high modulation ratio between signal and pump beams, it was considered advantageous to injection-lock the laser array at a larger than conventional angle (>4°) which corresponds to a higher-order resonant condition for constructive interference in the array far-field. This resulted in the locked portion of the output being highly angularly separated from the free-running array output, ensuring that all the power in the pump beam was derived from the injection locking process. The far-field pattern of the free-running array output consisted of a broad output between the angle of ±3.5° of the array facet, but after injection a large spike appeared at an angle of 10° to the array facet which contained a significant fraction of the array output power (Fig. 3). The locked beam was then spatially separated from the rest of the array output using a prism positioned at the array far-field generated by the cylindrical lens. This beam was then directed toward the $BaTiO_3$

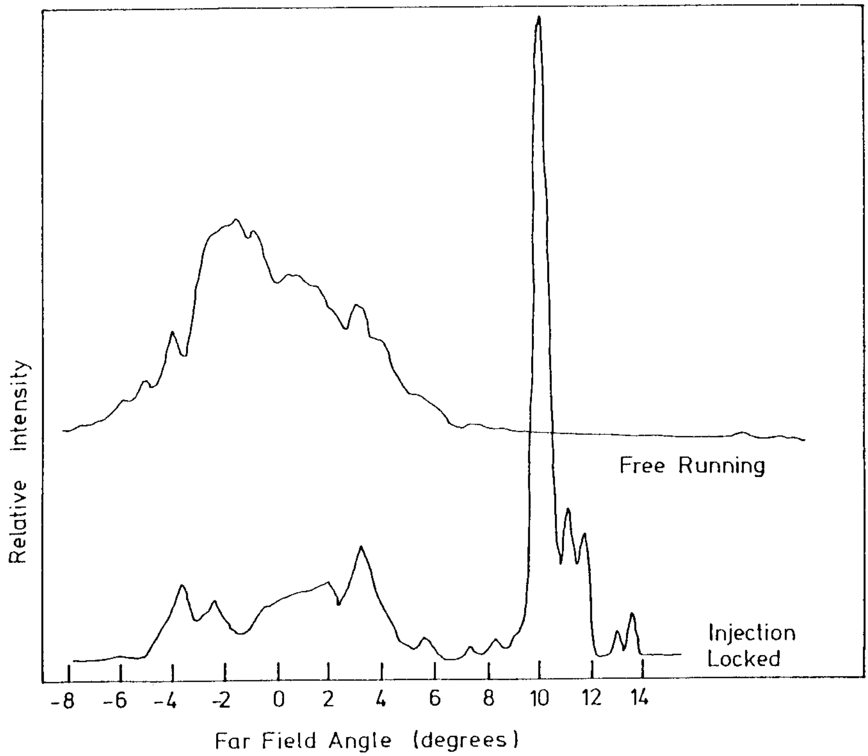

Fig. 3. Far-field patterns of free-running and injection locked array output. The injection locked spike contains approximately 190 mW.

crystal, via a spherical focusing lens, such that it entered the crystal at Brewster's angle. The signal beam was directed into the $BaTiO_3$ crystal at an angle of 20° to the pump beam resulting in a crossing angle of 5° within the crystal and an angle of 17° between the grating k-vector and the c-axis.

Initial work was carried out to investigate how the amount of locked power varied as a function of the injected power. This was done by placing a variable neutral density filter in the injecting beam path and monitoring the maximum power obtainable in the injection locked spike as the injection power was altered. For all injection powers less than 20 mW, there was an approximately linear relationship of the form

$$P_{\text{lock}} = 10.4\, P_{\text{inj}} + 20\,. \tag{2}$$

When the injecting beam was blocked, the power extracted at the prism dropped to less than 15 mW, suggesting that practically all of the power in the spike originated from the injection locking process. Assuming complete coherence between pump and signal beams, the power in the amplified signal beam is governed by

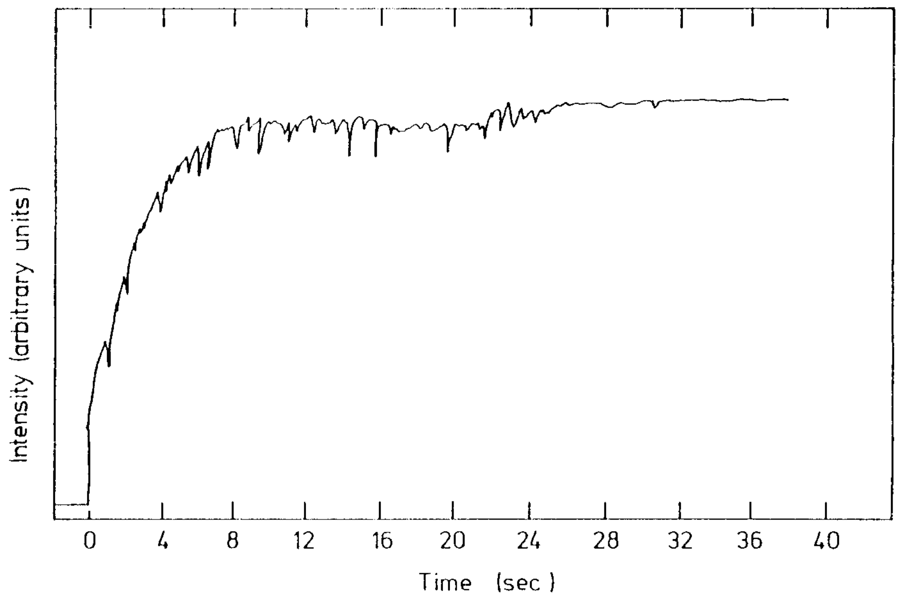

Fig. 4. Measurement of the power in the signal beam as a function of time. The signal beam is switched on at $t = 0$.

$$P_s(l) = P_s(0)\,\frac{(1 + r)\,e^{\Gamma l}}{1 + re^{\Gamma l}}, \tag{3}$$

where $P_s(l)$, $P_s(0)$ = amplified signal beam power, incident signal beam power, respectively.

In order to obtain the maximum power output from the system, the optimum splitting ratio between the injected power and signal beam power was calculated from Eqs. (2) and (3), and experimentally measured values of Γl giving powers of 21.9 mW and 20.4 mW for signal and injecting beams, respectively. This resulted in an injection locked pump beam power of 188 mW and a signal beam power of 18.6 mW, both measured at the crystal face. The array was operated at a current of 1.63 A which corresponds to an output power of 650 mW. With the pump beam blocked, the unamplified signal beam was measured as 13.4 mW which grew to 108.3 mW when the pump beam was unblocked. These values correspond to a gain of 8.1 for the signal beam, and a 49% depletion of the pump beam. The response time for the coupling process was measured to be 20 seconds (see Fig. 4). Reasonably long term stability (>10 minutes) was regularly observed with power fluctuations of less than 10%, but the coupling was often erratic, possibly due to a small amount of feedback into the master laser even with the high optical isolation being used. With improved mechanical and optical isolation it is hoped that more stable, higher-power beam combination should be possible. In order to assess the spatial properties of the signal beam, it was focused through a 25-μm pinhole using a

10x microscope objective and the power transmitted monitored with and without the pump beam blocked. The pinhole size selected corresponded to approximately 1.5 times the calculated waist size at the focus, thereby ensuring that any change in beam profile would be observed. These measurements demonstrated a decrease of 3% in the transmission ratio for the amplified beam over the nonamplified which suggests that there is a negligible change in beam profile taking place during the amplification process.

Significant improvements in output power from the system can be obtained by simple antireflection coating of the beam handling optics. Correction for Fresnel losses suggest that an overall array to single-mode output beam transfer efficiency of 33% should be obtainable, corresponding to powers of more than double our current values (>220 mW) for 650 mW of array output.

The scaling of this technique to the combination of multiple arrays has recently been demonstrated, using two 200-mW gain-guided laser arrays locked to the same single-mode master laser. The locked outputs from both devices were coupled in $BaTiO_3$ and an energy transfer efficiency in excess of 80% was obtained, with a diffraction limited performance.[25] In addition, coherence measurements[26] on the outputs from two laser arrays locked to the same master laser have demonstrated a relative coherence of 0.96 ± 0.06 which suggests that, correcting for Fresnel losses and absorption in the crystal, near 100% energy transfer should be attainable.

The number of slave laser amplifiers that can be locked to a given master laser is presently limited by the power available from a single-mode, diffraction limited source which can be used as a master laser. Since a finite amount of power is required to phase lock each slave amplifier, the number of devices which can be efficiently locked is restricted. This problem can be circumvented by use of a cascaded locking scheme which involves the use of an intermediate amplification stage between the master laser and slave laser amplifiers.[31] Using a configuration of this type, the amount of power available in the master laser output is almost unlimited, enabling the phase locking of many amplifier devices and leading to the possibility of generating very high power, all semiconductor laser outputs.

An alternative method for achieving the combination of the outputs of multiple laser arrays is the phase conjugate master-oscillator power-amplifier (PC MOPA). If a diffraction limited signal beam is split into a number of beams at a suitable beam splitter, each of which is then amplified and phase conjugated, the nature of the phase conjugation process will ensure that all phase aberrations generated in the amplification process are removed and coherent combination of the conjugates will take place at the initial beam splitter. It has been demonstrated[27] using high-power Nd:YAG amplifiers that phase conjugation will allow power scaling between physically separate amplifiers with no need for interferometric path length matching as long as the phase conjugation of the separate beams takes place in the same nonlinear interaction.

The conventional PC MOPA[28] involves the injection of a single-mode diode laser beam into a diode array amplifier and phase conjugation of output back through the

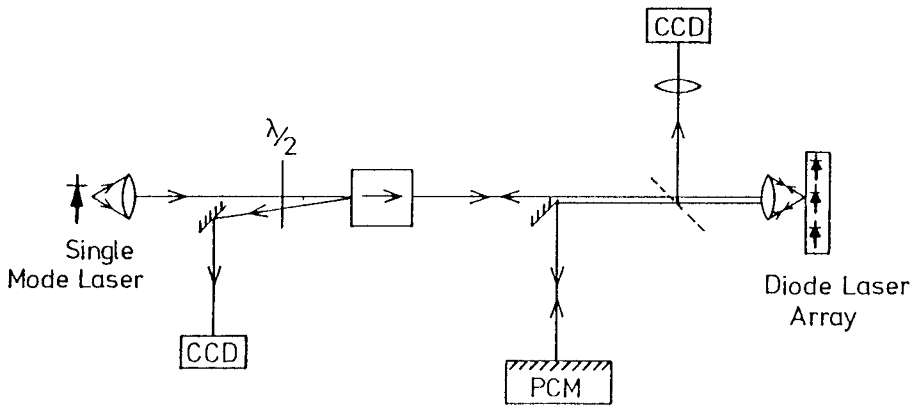

Fig. 5. Experimental configuration for reflection geometry phase conjugate master oscillator-power amplifier. The Faraday isolator acts as an output coupler for the system, rejecting the phase conjugate return beam at a small angle to the injection axis. The phase conjugate mirror (PCM) consists of a $BaTiO_3$ with a external mirror loop.

amplifier, thus removing all the optical path errors accumulated on the first pass. The diode amplifier in this case is a back and front facet antireflection coated diode array. These devices are technically difficult to manufacture, requiring good optical access to both front and rear facets, and considering the very large output divergence perpendicular to the array junction, this presents significant problems in adequate heat sinking for the active region. (A previous report noted the failure of several stripes of the amplifier device during operation of their PC MOPA.) In order to avoid the necessity of optical access to both facets, we have developed a reflection geometry PC MOPA which greatly reduces the problems associated with heat sinking of the laser array.

A schematic of the experiment is shown in Fig. 5. The master oscillator used was a Sharp LTO16 MD which operated on a single longitudinal and single transverse mode at a wavelength of 804 nm. The power amplifier was a commercial 10-stripe, gain-guided laser diode array (SDL-2430-G) with no special coatings. It was mounted on a temperature controlled heatsink and the temperature adjusted such that the wavelength of the peak of the array gain curve matched that of the master oscillator. The injection locking and extraction of the injection locked output was similar to that described in the previous experiment except that the master laser was injected at the more conventional angle of 4°. The injection locked output was directed toward a $5 \times 5 \times 5$ mm $BaTiO_3$ crystal in a self-pumped external ring phase conjugate geometry.[29] The phase conjugate power was monitored using a reflection from an optical flat.

The Faraday isolator used (Optics for Research IO-5-NIR) rejected the remaining array output at a small angle to the master oscillator beam axis, allowing it to act as the output coupler for the diode array amplifier. This output was monitored using a CCD camera and video analyzer.

In the injection locking process, a small signal beam is injected on one side of the array output facet and is amplified to saturation within one round trip of the Fabry–Perot amplifier. Subsequent reflections see a unity roundtrip gain, cavity losses being introduced as an output from the low reflectivity output coupler. Because of the multipass nature of the Fabry–Perot amplifier scheme, the injected signal beam fills all the active gain region of the diode array resulting in a very efficient transfer of the available gain from the diode array amplifier into the injected signal beam. In order to obtain optimum gain saturation of the diode array amplifier, it is necessary to choose the front facet reflectivity so as to increase the lasing threshold of the device to prevent the oscillation of the free-running modes of the laser array competing for the available gain of the array amplifier at high operating currents. Unfortunately, an antireflection coated diode array was not available at this time, so the array was operated close to threshold so as to suppress self-oscillation of the free-running modes of the array in order that it would simulate the operation of a diode array amplifier as closely as possible.

When the master oscillator output was initially injected at an angle of 4° into the diode array cavity, the system acted as a conventional injected locking scheme, generating a diffraction limited lobe in the far field containing in excess of 65% of the array output. For the initial investigations, the array was operated at 1.2 I_{th}, corresponding to a free-running array output of 45 mW. The injection locked lobe was spatially separated and directed toward the phase conjugate mirror. After a characteristic response time of approximately 10 seconds, the phase conjugate reflectivity began to grow and an additional lobe appeared in the far field at an angle of $-4°$, corresponding to the amplification of the phase conjugate beam. The phase conjugate lobe intensity then grew at the expense of the injection locked lobe intensity, until the phase conjugate reflectivity of the system became saturated at a value of ~20%. At this point, the power in the phase conjugate lobe was roughly equal to that in the injection locked lobe. When saturation of the phase conjugate reflectivity had been reached, the intensity of the output from the system, contained in the phase conjugate lobe, remained constant to better than 1%. If the phase conjugate reflectivity was disrupted by, for example, a small movement of the crystal, the same characteristic growth in the output from the system was repeated as the phase conjugate grating reformed.

Figure 6 shows the far-field pattern of the array when the master-oscillator beam was injected with and without the phase conjugate feedback present. The phase conjugate output lobe shows a full-width, half-maximum of 0.61° which compares to the diffraction limit of 0.59° for a uniformly illuminated aperture 100-μm wide. At higher injection powers, the phase conjugate lobe began to broaden slightly, growing to a maximum value of 1.8 times the diffraction limit for an injected power of 9 mW at the array facet. The longitudinal mode spectrum was monitored in the MOPA configuration and showed a predominantly single-mode operation with frequencies corresponding to the free-running modes of the amplifier array suppressed by ~14 dB from the main mode. On increasing the array injection

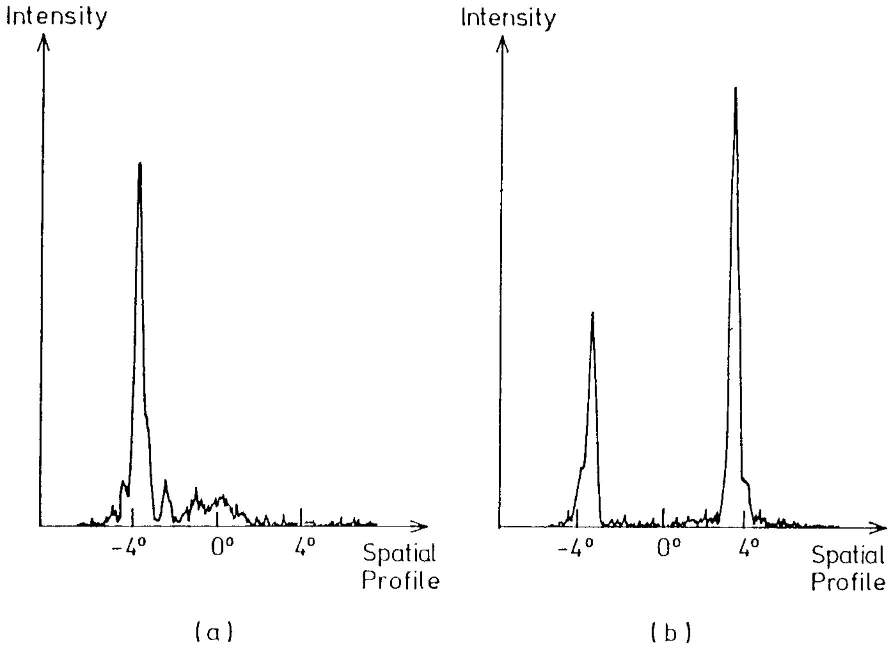

Fig. 6. Array far-field patterns for (a) conventional injection locking with no phase conjugate feedback and (b) operation as PC MOPA. The right-hand spike represents the diffraction limited PC MOPA output and the left-hand spike represents the input for the self-pumped phase conjugate mirror.

current, the twin lobe structure was maintained but the central regions of the far-field pattern began to fill in as the free-running modes of the array began to compete. At an injection current of 1.5 I_{th}, corresponding to an array output power of 100 mW, ~0.24 of the array output was outside of the two locked lobes. This problem could easily be solved by antireflection coating the front facet of the array, thus preventing the appearance of the undesirable self-oscillation.

The output of the system was investigated as a function of the injected master oscillator power, varying the injected beam intensity between complete gain saturation of the amplifier, occurring for injected power in excess of 5 mW, and weak injection locking conditions which occur for injected powers of less than 1 mW. The injected master oscillator power was controlled by means of a variable neutral density wheel in order to avoid the wavelength changes which accompany changes in operating current. These injection powers were required for the array used operating at 1.2 I_{th} but would be significantly lower for the case of a front facet antireflection coated array amplifier. The ratio of the intensities of the phase conjugated (output) lobe to the injection locked lobe as a function of the injected power is shown in Fig. 7. This behavior can be explained in terms of gain competition between the initial injected beam and the phase conjugate beam within the array active region.[30] For the case of high injected powers, the gain within the array is totally saturated and practically all the amplifier output is contained within

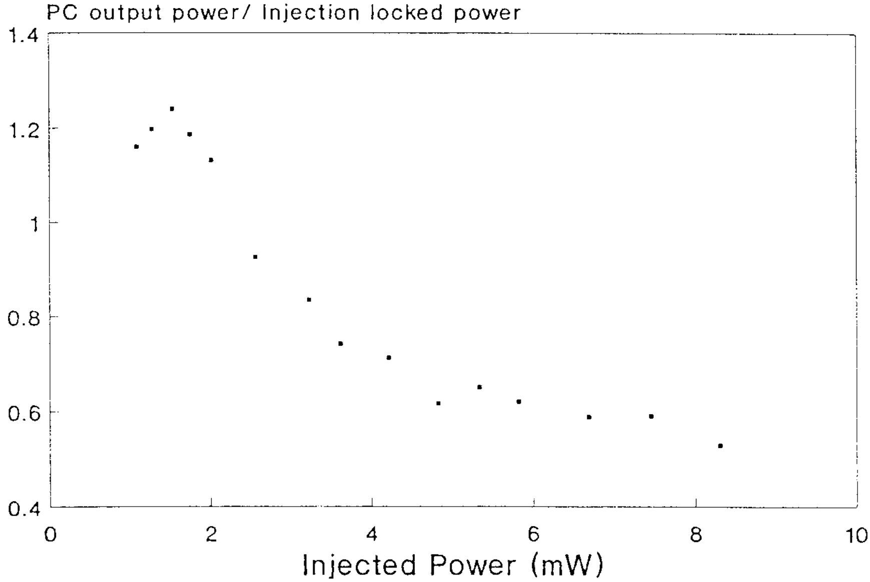

Fig. 7. The ratio of power in the injection locked spike to the power contained in the phase conjugate output as a function of the injected power. Gain competition between the injected signal beam and the returning phase conjugate signal gives rise to the observed profile.

the injection locked spike. This leads to efficient phase conjugation, but the back-traveling beam sees little gain within the amplifier since it has to compete with a much stronger injected beam. As the injected power decreases, the locking efficiency of the array drops, leading to a smaller fraction of the amplifier output being contained within the injection locked spike. The phase conjugate beam is therefore less intense, but sees less gain competition within the amplifier on the return pass, resulting in a higher gain. The two factors of gain saturation and injection locking efficiency compete to generate the profile shown by Fig. 7. This is in reasonable agreement with the more detailed theoretical analysis of the gain processes involved in the phase conjugate MOPA given in Ref. 28. For the configuration described, the peak output was 26 mW for an injected power of 1.50 mW, corresponding to a signal gain of 13 dB. For injected powers of less than 1 mW, the free-running modes of the laser were sufficient to disrupt the phase conjugation process, and the phase conjugate reflectivity dropped to zero. With the use of specifically designed antireflection coated array amplifiers, it should be possible to couple the outputs of several devices to generate a high-power, diffraction-limited beam.

In conclusion, photorefractive techniques for the brightness enhancement of high-power diode laser devices have been demonstrated to show great promise for the generation of powerful diffraction-limited beams from all semiconductor systems. Near 100% photorefractive coupling efficiencies should be obtainable between amplifiers locked to the same master laser using suitably antireflection coated optics. Great improvements in the efficiency and power available from such systems can be obtained by the development of specific high-power, semiconductor amplifier devices which are able to effectively suppress the loss of optical power to self-oscillation. Extension of these photorefractive phase locking and combining techniques to the high-power diode laser bars and new generation of surface emitting devices will hopefully yield interesting results in the future.

Acknowledgments

We are grateful to the Science and Engineering Research Council for financial support of Stuart MacCormack.

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