Near-diffraction-limited single-lobe emission from a high-power diode-laser array coupled to a photorefractive self-pumped phase-conjugate mirror

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Details of a 20-stripe, 1-W diode-laser array coupled to a photorefractive self-pumped phase-conjugate mirror in a self-injection-locking geometry are discussed. Single-lobe emission is observed, with 75% of the array output in an ∼2.2 times diffraction-limited beam, for array output powers of as much as 450 mW.

Linear phased laser-diode arrays provide a compact, high-power, high-efficiency source of monochromatic light and have found many applications in all-solid-state minilaser and microlaser systems. Unfortunately, the preferred modes of operation of free-running conventional gain-guided phased-laser-array operation involve the simultaneous oscillation of many transverse array modes,[1-3] which results in an undesirable broadened twin-lobe output in the far field that is generally several times the diffraction limit of the emitting region. This leads to poor focusability for the array output, which in turn limits the efficiency of launching into single-mode fibers, coupling into planar waveguides, and longitudinal pumping of solid-state microlasers. The use of selective external-feedback techniques to obtain single-lobe operation of a laser array has been demonstrated with two main techniques: suppression of the higher-order transverse array modes by means of spatial filtering within an external cavity[4,5] and the use of selective angular feedback in order to self-injection lock the array operation effectively.[6-8]

Optical phase conjugation presents itself as an ideal solution for external self-injection-locking configurations since the requirements of accurate mirror alignment and exact retroreflection of the array output back into the array stripes are automatically satisfied in the phase-conjugation process. The coupling of laser-diode arrays to several different forms of phase-conjugate mirrors has previously been described,[9] which gives rise to a broad single-lobe emission and frequency locking between two arrays for the case of the dual-pumped phase-conjugate mirror and single-longitudinal-mode operation of an array when it is coupled to an external-ring self-pumped phase-conjugate mirror[10] (SPPCM). In addition, mode locking and frequency tuning of a laser array coupled to a photorefractive passive SPPCM have been demonstrated.[11] In all these cases the output powers available were severely limited owing to the competition between the external-cavity selected mode and free-running array modes that occurs at higher output powers. In this Letter we present details of a 20-stripe high-power diode-laser array coupled to a simple external-ring SPPCM in a self-injection-locking geometry that emits in a near-diffraction-limited, single-lobe output.

The array used was a commercial, 1-W gain-guided device (Spectra Diode SDL 2462-P1) operating near a wavelength of 808 nm. In order to initiate the self-pumped phase-conjugation process, we found it necessary to lock externally the array to single-longitudinal-mode operation by means of a conventional injection-locking procedure.[12] The experimental setup is shown in Fig. 1. The output of a single-mode diode laser (Sharp LTO 17 MD) was injected down the path of one lobe of the free-running array profile, at an angle of approximately +4° to the array normal, through a Faraday isolator in order to prevent output from the array from returning along this path and

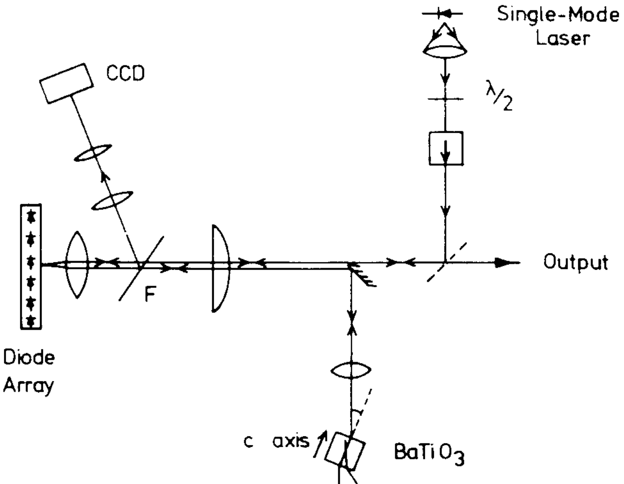

Fig. 1. Apparatus setup for coupling of the laser array to the SPPCM. The array output was incident upon the crystal at an angle of 30°, and the external loop angle φ was set at 25°. The far-field pattern was monitored with a charge-coupled-device (CCD) camera by using a reflection from optical flat F. When the SPPCM was well established, the injection-locking apparatus could be removed to allow full access to the array output.

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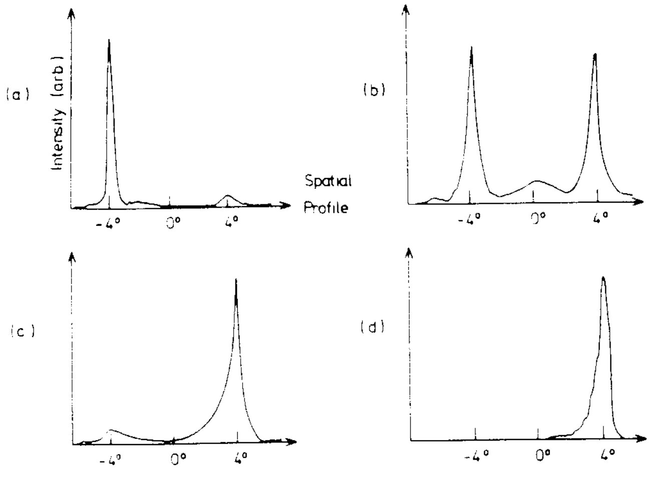

Fig. 2. Far-field patterns of array for (a) the conventional injection locking process, (b) injection locking with SPPCM feedback, and (c) the array coupled to the SPPCM with no external injection locking. (d) Illustrates the profile of a single lobe generated when the far-field pattern of four experimentally observed array eigenmodes are mixed. The best experimental fit is obtained when the bulk of the composite profile consists of the higher-order array eigenmodes.

causing instabilities in the master laser. The injected power at the array facet was measured to be 25 mW, and the array was operated at $1.1I_{\mathrm{th}}$, which ensured that the injection-locking process was completely saturated.[13] This resulted in the array emission's appearing in the opposite lobe and the array's switching to single-longitudinal-mode operation [Fig. 2(a)]. The array output beam was then picked off and directed to an external-ring SPPCM, which consisted of a 5 mm × 5 mm × 5 mm $BaTiO_3$ crystal and two high-reflectivity mirrors. A lens of focal length 125 mm was used to ensure that the spot sizes of the beams crossing within the crystal were correctly matched, and an optical flat was used to monitor the phase-conjugate reflectivity of the loop.

Initially, the array far-field pattern consisted of a large spike at an angle of −4° to the array normal that contained a large fraction of the output power. After a characteristic response time of approximately 5 s, corresponding to the buildup time for the photorefractive grating within the ring SPPCM, the phase-conjugate reflectivity of the SPPCM grew, and an additional spike appeared at an angle of +4° to the array normal that resulted from the amplification of the phase conjugate of the injection-locked output beam. For a phase-conjugate reflectivity of 2.5%, both lobes were of equal intensity, and the SPPCM reflectivity appeared to become saturated [Fig. 2(b)]. The injecting beam was then blocked, and the majority of the array output was instantaneously transferred into the +4° lobe [Fig. 2(c)], which resulted in the array output's being easily accessible in a single-beam output. In addition, a small spike was observed at an angle of −4° to the array facet, which corresponds to the signal beam for the phase-conjugate mirror. It was then possible to increase gradually the array driving current, with the dynamic nature of the phase-conjugate grating enabling the SPPCM to respond to the change in lasing wavelength caused by the change in driving current. The maximum rate of change was found to be approximately 10 mA/s, which corresponds to a wavelength shift of 0.005 nm/s. With no apparent broadening in the far-field spike, it was possible to increase the array current to $2.1I_{\mathrm{th}}$ (corresponding to an array output power of 450 mW), at which point the self-injection-locking process became unstable and there was a washout of the SPPCM grating followed by the array's returning to its free-running far-field pattern. FWHM of the far-field spike generated under the phase-conjugate self-injection-locking scheme was measured to be 0.67°, which corresponds to 2.2 times the diffraction limit for the array emitting region, with 75% of the the array output power being contained in this spike.

The longitudinal-mode spectrum of the array was monitored at each stage of the procedure. For all situations when the single-mode laser was being injected there was a pronounced array single-longitudinal-mode operation with side-mode suppression well in excess of 20 dB. On blocking the injecting beam, the longitudinal-mode spectrum became erratic with many modes growing and fading over a time of a few minutes before the mode pattern settled into a stable six-mode output that was almost identical to that of the free-running array pattern. The asymmetric nature of the far-field lobe when the array was coupled to the SPPCM suggests that the array is simultaneously operating on a number of array transverse modes. The positioning of the far-field pick-off mirror, initially set to pick off the injection-locked lobe at $\theta = -4°$, will only extract and feed back the array far-field emission corresponding to $\theta < -3°$ and in so doing increase the relative modal gain for those array modes, with a significant fraction of their output at larger emission angles. Current broad-area approaches to the determination of array transverse mode structures[1–3] suggest that for a gain-guided array of N stripes, the array mode of order m is characterized by two main lobes radiating at angle $\pm\theta_m$, where

$$\sin\theta_m = \frac{m\lambda}{2x_0}$$

(x_0 is the total width of the array), and additional smaller lobes at $\pm\theta_{2N-m}$. For the free-running array, the modal gains for transverse modes of order $m > N$ are approximately equal, so the selective feedback observed for the higher-order modes, owing to their wider far-field emission angles, will cause the array to oscillate on these modes preferentially. The observed profile of the array output when coupled to the SPPCM shows good agreement with the profile that is generated from the superposition of a number of high-order array transverse modes as illustrated in Fig. 2(d). Unlike in the results presented in Ref. 9, we observed no tendency for the laser to operate on a single longitudinal mode.

The output from this system was very stable (<1% intensity fluctuations) and relatively insensitive to external vibration. It was also possible, owing to the inherently long storage time of the SPPCM geometry, to block the phase-conjugate path for periods of a few minutes without observing any degradation in the output beam when the path was subsequently unblocked. When the path was blocked for longer periods than this, the phase-conjugate reflectivity of the system dropped below the threshold needed to sustain the injection-locked feedback, and the array returned to its free-running profile. Once the SPPCM had been established, single-lobe operation was maintained until the feedback process was actively prevented.

In our experiment, we have been unable to observe a self-starting ring SPPCM without the use of an external locking laser to control the initial output from the array. Previous results,[9] however, have demonstrated that a free-running array operating close to its threshold is capable of self-starting the external-ring SPPCM and generating phase-conjugate reflectivities of as much as 10%. This would enable the use of a SPPCM self-injection-locking scheme with no need for the single-mode injecting laser, thus simplifying the process significantly. We believe that the use of the injection-locked laser output as the pump beam in the SPPCM allows the threshold for efficient phase conjugation to be reached more easily owing to the elimination of the competition between multiple grating formation that occurs with the multilongitudinal output associated with the free-running array. When the injecting beam is removed, the free-running modes, being approximately Bragg matched, are able to diffract parasitically from the photorefractive grating to initiate the phase-conjugation process. The effective reflectivity of the SPPCM varies with the wavelength of the incident light, with the modes closest to that of the injection-locked spike seeing a higher degree of feedback. The free-running modes of the laser then overwrite the initial grating so that each mode then sees equal phase-conjugate reflectivity, and hence the longitudinal mode structure returns to that of the free-running array.

In conclusion, we have presented a scheme involving a diode-laser array coupled to a photorefractive self-pumped phase-conjugate mirror in a self-injection-locking geometry. Single-lobe outputs of 2.2 times the diffraction limit have been obtained containing 75% of the array output up to powers of 450 mW. The injection-locking characteristics for diode-laser arrays depend strongly on the lasing threshold current of the device, which is governed by the front facet reflectivity. For optimum injection-locking results the array should be operated close to its threshold so as to suppress the free-running array modes of the laser cavity. Therefore, the use of a partially antireflection-coated array should considerably increase the output powers at which the self-injection-locking process becomes unstable and should permit higher single-lobe outputs from the system. The coupling of two or more laser arrays in a cascaded injection-locking[14] process in order to obtain much higher single-beam output powers should be possible by using the ability of phase conjugation to retrace exactly an optical path through a complicated system, and this presents a promising technique for the passive combination of the outputs from multiple laser arrays or diode-laser bars into near-diffraction-limited, single-lobe outputs.

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