Efficient amplification of a single-mode laser diode by photorefractive beam combination using an injection-locked diode-laser array pump

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Powers in excess of 100 mW have been obtained in a near-diffraction-limited, single-mode laser-diode output by photorefractive two-beam coupling in $BaTiO_3$, using an injection-locked 1-W diode-laser array as the pump source. Signal gains of as much as 8.1 are obtained, corresponding to pump transfer efficiencies of 49%. Calculations suggest that powers as high as 225 mW should be obtainable, given suitably antireflection-coated optics.

The use of photorefractive two-beam coupling as a method of coherent beam amplification has been well documented.[1] The photorefractive effect occurs in a range of electro-optic materials through the spatial modulation of photocurrents, induced by nonuniform illumination of the material. In two-beam coupling, an intensity interference pattern is generated within the material, which, by a process of charge excitation, migration, and subsequent retrapping, gives rise to a modulated space-charge field. This in turn, through the Pockels effect, gives rise to a modulated refractive-index grating. For the case on which photocarrier diffusion is the main charge-transport mechanism, as for $BaTiO_3$ and strontium barium niobate, there is an additional 90° spatial phase shift between the index grating and the interference grating. This leads to a nonreciprocal transfer of energy from one writing beam to the other. In addition, theoretical and experimental evidence[2] shows that there is no phase cross talk between pump and signal beams, so the temporal quality of the signal beam is preserved during the amplification process. This property suggests that photorefractive materials provide an ideal medium in which to perform coherent combination of the power from two (or more) injection-locked lasers in order to obtain high-power outputs with good spatial and temporal qualities.

The attainment of high-power, diffraction-limited output from semiconductor lasers is currently the subject of great interest for many applications. The output from a single-stripe, single-longitudinal-, single-transverse-mode semiconductor laser is diffraction limited, but power outputs from even the highest-power single-stripe diodes do not currently exceed the 100-mW level because of problems of heat dissipation from the lasing region and laser facet damage. Diode-laser arrays and bars present a solution to the problem of higher powers, but their output is generally far from diffraction limited, leading to a loss of efficiency in applications such as launching into monomode optical fibers and longitudinal pumping of solid-state microlaser systems.

Previously, the possibility of injection locking and combining of two or more single-stripe diode lasers by means of a binary phase grating had been demonstrated,[3] 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.[4,5] High coupling efficiencies have been obtained by the use of a $BaTiO_3$ crystal in place of the fixed grating, transfer efficiencies as great as 80% having been reported between the outputs from two locked single-stripe diode lasers.[4] 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.[5] Two-beam coupling techniques have also been suggested for the coherent combination of a series of locked laser arrays into a diffraction-limited beam.[6] 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 high pump powers necessary for large gains for the signal beam. In this Letter we describe and demonstrate the use of two-beam coupling to combine coherently the outputs from a single-stripe diode laser and an injection-locked 20-stripe, 1-W diode-laser array in order to obtain a high-power, near-diffraction-limited output.

A necessary criterion for achieving good power transfer efficiencies in two-beam coupling is that the two interfering beams have a time-varying relative phase relationship that is much smaller than the photorefractive response time of the material being used. In the case of $BaTiO_3$, at the typical intensities used in this experiment (10 W/cm^2 at 807 nm) the response time is approximately 15 sec at room temperature.[7] This relative phase stability between pump and signal beams is achieved by injection locking[8] of the diode-laser array (pump) with a fraction of the single-stripe (signal) output beam. Current models[9] suggest that diode arrays behave as weakly perturbed Fabry–Perot amplifiers under suitable injection conditions, result-

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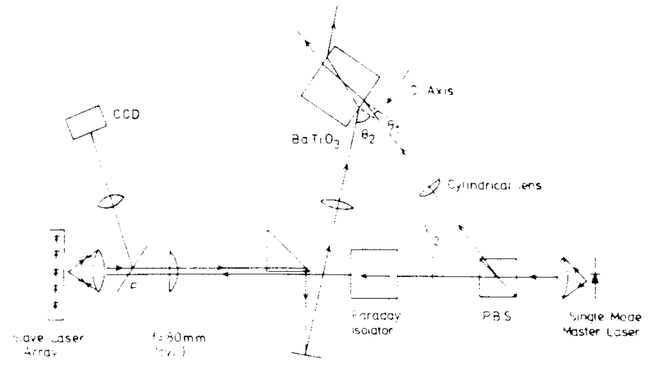

Fig. 1. Experimental setup for injection locking and beam combination. The single-mode master-laser output is split at a polarizing beam splitter (P.B.S), one fraction being injected into a slave-laser array and the other acting as the signal beam. The array far-field pattern is monitored by reflection from an optical flat (F), using a charge-coupled device camera (CCD). Pump and signal beam angles at the crystal are $\theta_1 = 68°$ (Brewster's angle) and $\theta_2 = 48°$, respectively.

ing in a large fraction of the array output's being emitted at the same frequency and at constant phase with the injected signal beam. At the injection powers described in this Letter, the locking was in the nonsaturated[10] regime, resulting in the power emitted from the array at the locking frequency being proportional to the amount of injected power.

Figure 1 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 of power 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 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° by 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 injection of a horizontal line focus at an angle of 10° into half of the laser array output facet. The far-field pattern of the array was monitored with a change-coupled device 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°) corresponding to a resonant condition for an integral number of passes through the array cavity. This resulted in the locked portion of the output's being highly angularly separated from the free-running array output, ensuring that all the power in the pump beam was generated in 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 that contained a significant fraction of the array output power (Fig. 2). The locked beam was then spatially separated from the rest of the array output by a prism at the far field generated by the cylindrical lens. This beam was then directed toward the $BaTiO_3$ crystal, through 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.

An initial study 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 of less than 20 mW there was an approximately linear relationship of the form

$$P_{\text{lock}} = 10.4 P_{\text{inj}} + 20. \tag{1}$$

When the injecting beam was blocked, the power extracted at the prism dropped to less than 15 mW, suggesting that practically all the power in the spike originated from the injection-locking process. Ne-

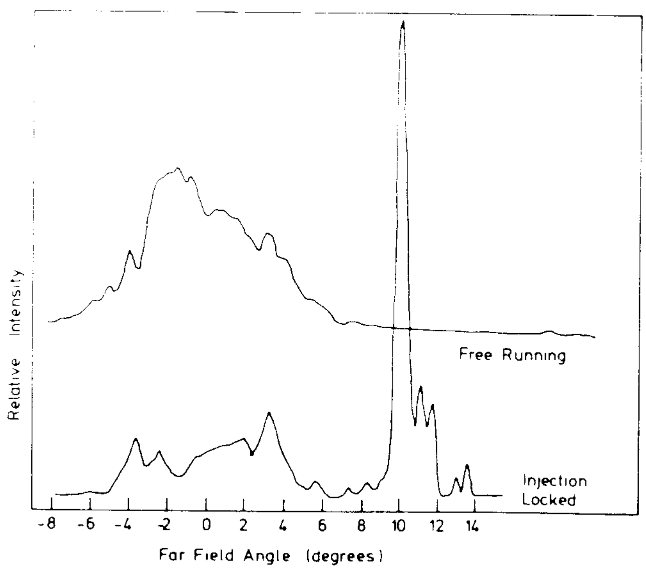

Fig. 2. Far-field patterns of the free-running and injection-locked array output. The injection-locked spike contains approximately 190 mW of power.

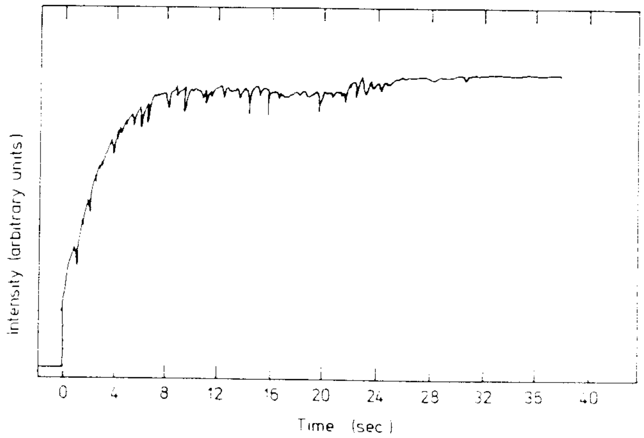

Fig. 3. Measurement of the power in the signal beam as a function of time. The signal beam is switched on at $t = 0$.

glecting Fresnel losses and absorption in the crystal, the power in the amplified signal beam is governed by

$$P_A = P_I \frac{(1 + r)\exp(\Gamma l)}{1 + r \exp(\Gamma l)}, \tag{2}$$

where r is the beam intensity ratio (I_s/I_p), Γ is the two-beam coupling gain coefficient, l is the effective interaction length, and P_A and P_I are the amplified signal beam power and the 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. (1) and (2) and from experimentally measured values of Γl, giving powers of 21.9 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 18.57 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 13.43 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 sec (see Fig. 3). Reasonably long-term stability (>10 min) was regularly observed with power fluctuations of less than 10%, but the coupling was often erratic, possibly because of 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 stabler, high-power beam combinations should be possible.[11] In order to assess its spatial properties, we focused the signal beam through a 25-μm pinhole, using a 10× microscope objective and the power transmitted monitored with and without the pump beam blocked. 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.

In conclusion, we have demonstrated coherent energy transfer between an injection-locked high-power diode-laser array and a single-stripe diode laser by two-beam coupling in $BaTiO_3$. With no antireflection-surface optics used for beam handling, powers in excess of 108 mW have been obtained in a near-diffraction-limited beam. Corrections for Fresnel losses suggest that an overall array to single-mode output beam efficiency of 21% should be obtainable, corresponding to powers of more than double our current values (>220 mW) from a single 1-W device. This technique is also scalable to the locking and combining of multiple high-power laser arrays, the only limitation being the amount of power available in the single-stripe locking beam. This is the direction of our future activity.

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