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Efficient Laser Performance Using a Microoptic Based Pump Source

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Abstract

A 19% wall plug efficient cw 3.7 watt TEM_{00} Nd:YVO_4 laser was demonstrated using a GaP microlens-coupled diode bar pump. Pump and solid-state laser scaling will be discussed.

Introduction

Longitudinal diode pumping, especially at low power levels, has yielded the most efficient solid-state lasers. A challenge to developers of lasers for space applications has been to effectively scale longitudinal pumping sources employing diode bar devices in order to reach higher output powers while maintaining efficient performance. Another necessary attribute of a pump source is that it be simple to implement which translates to minimization of cost, weight, and volume of the overall device. Several approaches using gain guided bars have been demonstrated with various levels of success [1,2]. We recently reported a new solid-state laser pump device which uses an array of 100 GaP microlenses (formed on the surface of a GaP substrate) to collimate a diode bar composed of 100 single mode index guided diode lasers. The strength of our approach is that a single microlens array can efficiently collect and collimate all the index guided lasers from a diode laser bar array, assuming all lenses and laser devices are optimally positioned with respect to each other. Furthermore, the novel index guided laser diode bar design is in principle, as easily fabricated in volume as currently produced cw broad area emitter (typically 50-200 μm astigmatic emitters spaced over 1 cm) diode bar devices. The small difference in production cost between the two types of diode bar devices can be traced to a few more processing steps and a lower percentage yield in the index guided devices. In this paper we report our first results on the integration of a 10 watt index guided diode laser bar device with a GaP lens array for pumping a Nd:YVO_4 laser.

Microoptic Design and Results of Integration with the Diode Bar

As reported earlier [3], our lens arrays are composed of hyperbolic lenses placed on 100 μm centers with focal lengths typically ranging (depending on the design) from 200-300 μm. The vertical diameters of the lenses are currently set to 300 μm, while the horizontal diameters are limited to 100 μm by neighboring lenses. Although each lens on the array is truncated by 1/3 on either side, it can still accommodate the lower divergence of the diode emitter parallel to the diode junction (see Fig. 1). A single SDL-5410 100 mW index guided laser device typically has a single transverse mode which is diffraction limited from approximately a 1 x 3 μm emission aperture. The output divergence of these laser devices is nominally specified at better than 10 by 30 degrees FWHM. Our measurements have shown that some single mode laser diode devices are less divergent than specified in the slow axis which can result in output with greater than a 3:1 aspect ratio. A single lens from the array after application of an AR coating typically collects and collimates ~90% of the total emission from an SDL-5410. When this light is refocused with a 2.1 cm fl achromat (macrolens) we obtain a focused spot diameter which is approximately equal to the predicted size of ~240 by 80 μm ($1/e^2$). However, when using various combinations of bars and arrays we find that the spots, on average are ~2.5 times larger than the theoretical limit and that the throughput is between 80 and 90%. To obtain the highest throughput, a GaP lens array with a shorter focal length of 200 μm and the same 300 μm diameter was used. This improved the light collection efficiency to 94%, yet increased the focused spot size to 500 by 200 μm. Finally we note that when using a 2.1cm macrooptic, the effective NA of this source is 0.25, determined from the outermost emitters.

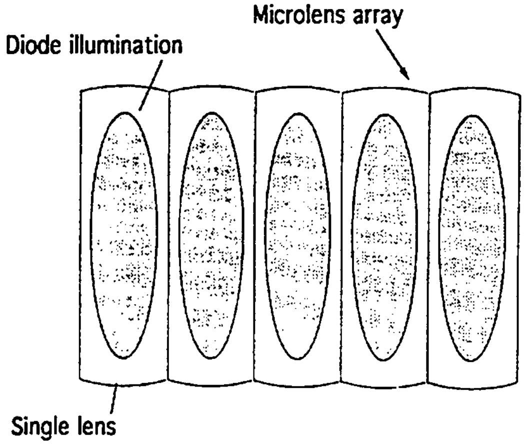

Figure 1. Illustration of adjacent lenses in array and illumination by diode bar.

A. Focusing Parameters

The final spot of the diode bar and lens system is the sum total of 100 individual Gaussian beams which overlap at the back focal point of the macrolens. The size and aspect ratio of this spot is determined by the initial size of the beams emitted by the individual diode element, the focal lengths of the micro and macrolenses, and the position of the microlens array from the diode bar. Since the emitters are index guided devices, it is reasonable to assume that the output at the facet of the emitters constitutes a beam waist for both the horizontal and vertical axes. If the lens array is placed at its focal length away from the diode bar then the final spot is an enlarged image of the intital spot with a manification factor given by the ratio of the macrolens and microlens focal lengths. A modification of the resultant 3:1 horizontal to vertical aspect ratio of the final spot can be accomplished by slight displacements of the microlens array from its focal length distance from the emitters. It can be shown that the final spot ω_1 in terms of the intial spot ω_0, micro and macro focal lengths f_1 and f_2, and the displacement of the microlens array Δz is given by

$$\omega_1 = \left[1 + \frac{\Delta z^2 \lambda^2}{\pi^2 \omega_0^4}\right]^{1/2} \frac{f_2}{f_1} \omega_0 .$$

Because of the strong dependence on ω_0, the displacement has a much greater effect on the vertical dimension since the intial vertical spot (~.5 μm) is 3 times smaller than the initial horizontal spot (~1.5 μm). Thus the vertical width can in principle be expanded to symmetrize the spot with a negligible increase in size in the horizontal plane. (For a fixed f_1 and f_2, the minimum spot size is, however, obtained with Δz equal to zero.) Reduction of the spot can be accomplished by decreasing the focal length of the macro lens, f_2. However, this increases the intersection angle of the overlapping beams which increases their effective cross sectional area. Generally this effect is not as important as is the decrease of the overlap depth, which is inversely proportional to f_1 and counteracts the advantage gained by reducing ω_1. Thus, an optimum balance between the spot size and overlap angle, in view of the laser material and resonator, must be reached in order to maximize the performance of the overall system.

B. Improvement of the Pump Spot

There are several factors that could cause the focused spot of the integrated diode bar and microlens array to exceed the theoretical limit. Because of the small size of the emitter the final spot is sensitive to alignment. For example, a 1 μm displacement in the vertical direction would result in a vertical translation of the focused image by one spot diameter. Most of the alignment problems can be traced to the diode array and lens array fabrication processes. Both devices are defined by photolithography at a submicron level of accuracy. In the case of the diode bar, deviation can occur when the diode chip is bonded to the heat sink. The mismatch in thermal expansion coefficients causes a bow (or smile) to occur over the 1 cm device upon cooling. In Figure 2, projected images of two bars are depicted, one with a 1 μm variation over the cm and the other with a 3.4 μm variation. Improvements are on going by vendors to solve the "smile" problem, which will ultimately affect device yield. Regarding lens array problems, we have sometimes observed expansion of the lens array by several microns following a high temperature annealing step used during fabrication. Tests are currently in progress to determine if the effect is systematic, in which case it can be corrected for by photolithographic mask modification. Despite the sensitivity of the system to these alignment issues, we have been able to get to within a factor of two from the theoretical minimum spot size (using the 1 μm smile bar), which indicates that we are physically able to align the bar and lens array on a submicron level. In addition, a problem separate from the displacement issues is the possible variation of the microlens focal length across the array. This issue could be related to the homogeneity of our milling process which is currently being improved.

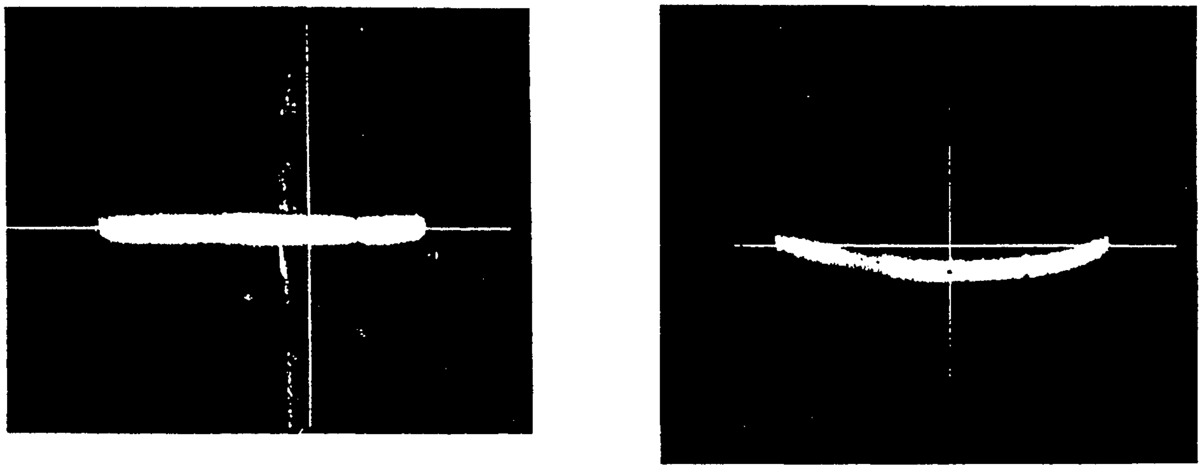

Figure 2. Projected image of two different100 element laser diode bars. The bar on the left has vertical deviation of 1 μm, while the bar on the right has a deviation of 3.4 μm.

Nd:YVO_4 Laser Results

The pump source described above was configured as shown in Fig. 3 for longitudinal pumping of a 3.7 mm path length 1% Nd:YVO_4 laser crystal with a flat HR coating on one surface and a flat AR coating on the other: with the available optics, the best performance was achieved with a 30 cm ROC 95% reflective output coupler and a cavity length of 15 cm. A performance curve for this resonator is displayed in Figure 4. We define the (effective) pump power as the amount of light passing through an adjustable iris that has been placed between the macrolens and the laser crystal and closed just until the output power of the laser drops. Despite the 94% throughput of the 200μm fl microlens array, we have observed that not all the light is focusable onto the mode of the laser. Using the iris we have measured the overall delivery efficiency of optical power from the bar to the laser mode to be 88%. For 8 W of effective pump power the laser yielded 3.7W of TEM_{00} output with a slope efficiency of 48% and an optical conversion efficiency of 46%, the highest yet demonstrated for a bar pumped device. At very low pump powers the output beam of the resonator is nearly circular. At the higher pump levels, thermal lensing causes the laser output mode to mimic the aspect ratio of the pump. Beyond 8 W of pump power the thermal lensing resulted in mode breakup and output power loss. If the resonator had remained stable for the full 10 W capability of the bar (~9 W effective pump) we would have expected an output of ~ 4.1 watts. We are currently examining alternative resonators and thermal management issues to remedy this problem.

To establish a baseline performance level, a Ti:sapphire laser was used to pump the same laser resonator with up to two watts of pump power. With all the pump light absorbed the optical slope efficiency reached 55%. Thus, after correcting for the 5% transmission of the bar pump light by the crystal, the microlens coupled diode bar is only 4% lower in efficiency than an ideal pump source for this particular cavity design. Based on the electrical power to the diode, the Nd:YVO_4 laser operated at 19% wall plug efficiency. To our knowledge, this is the highest efficiency multiwatt solid state TEM_{00} laser yet demonstrated. Greater efficiencies should be obtainable for these higher power end pumped systems if both the resonator and pump modes are reduced (as suggested in Fig. 4 by the 63% slope efficiency obtained with a smaller Ti:sapphire pumped resonator) and if the thermal effects can be adequately handled.

The output power of index guided sources have recently been extended to two hundred milliwatts [4] per emitter which implies that this technology could easily be upgraded to yield 20 Watts per bar output. We are currently examining this approach as well as increasing the number of bars to reach higher pump powers. We have assembled a 4 diode bar pulsed/cw device to be used for approximately a 1 mm mode diameter longitudinally pumped laser.

Summary

GaP microlens arrays have been successfully integrated with matching 10 watt index guided 100 element diode laser arrays. Nearly 90% of the light was collected and delivered to a spot of diameter 500 μm with an NA of 0.25 for pumping of a Nd:YVO_4 laser. 3.7 Watts of TEM_{00} output was obtained at 1.06μm at a wall plug efficiency of 19%.

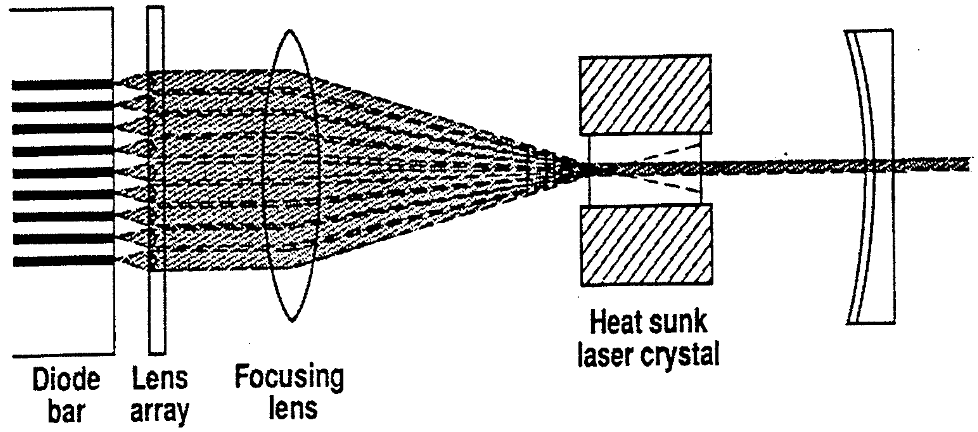

Figure 3. Diode bar plus microlens array configured to longitudinally pump a solid state laser.

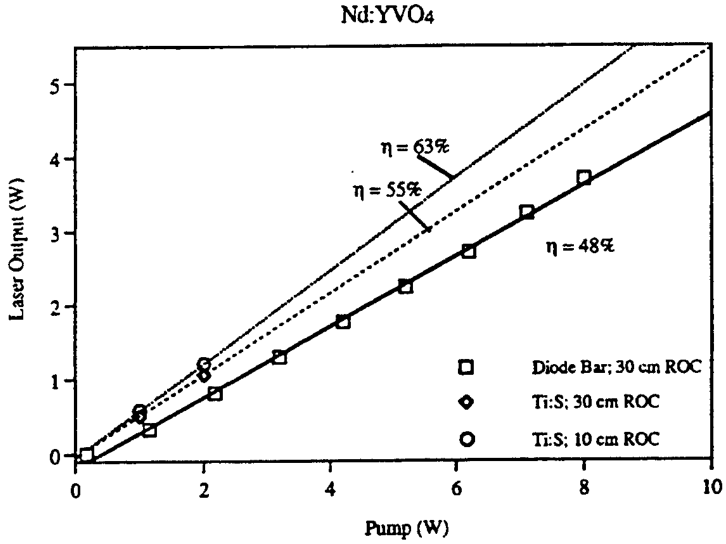

Figure 4. Nd:YVO$_4$ TEM$_{00}$ 1.06 μm laser output plotted against pump power incident on the HR face of the laser crystal.

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References

1. S. B. Hutchison, T. Baer, K. Cox, P. Gooding, D. Head, J. Hobbs, M. Keirstead, and G. Kintz "Advances of 3-10 Watt Average Power Diode Pumped Lasers", in Diode Pumping of Average-Power Solid State Lasers, G. F. Albrect, R. J. Beach, S. P. Velsko, Editors, Proc. SPIE 1865, 61-72 (1993).
2. S. C. Tidwell and J. F. Seamans, " 60 Watt, near-TEM$_{00}$, cw diode-end-pumped, Nd:YAG laser", in Diode Pumping of Average-Power Solid State Lasers, G. F. Albrect, R. J. Beach, S. P. Velsko, Editors, Proc. SPIE 1865, 85-92 (1993).
3. T. S. Rose, J. S. Swenson, and R. A. Fields, "High-Efficiency Longitudinal Diode Bar Pumping of Solid State Lasers", in Diode Pumping of Average-Power Solid State Lasers, G. F. Albrect, R. J. Beach, S. P. Velsko, Editors, Proc. SPIE 1865, 56-60 (1993).
4. Personal Communication D. Welch of SDL.

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