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Efficient Laser Diode Side Pumped Neodymium Glass Slab Laser

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Abstract—**We report efficient pulse operation of an Nd:glass slab laser side pumped by laser diode arrays. 7.5 mJ output and a slope efficiency of 29 percent were obtained with 35 mJ pump energy at 0.8 μm in 200 μs pulses. The wide absorption band at 0.8 μm and low laser loss in this phosphate glass allow for efficient pump light absorption and straightforward scalability to higher power.**

LASER diode arrays that emit near 800 nm are being widely used to pump neodymium and other rare-earth-based solid-state lasers [1]–[7]. In neodymium, the photon quantum efficiency for populating the $^4F_{3/2}$ state by pumping directly into the $^4F_{5/2}$ state is generally greater than 80 percent and substantially exceeds the comparable efficiency from broad spectrum flashlamps. Large semiconductor arrays have been built with electrical to optical efficiencies greater than 50 percent and with pulsed outputs of over 100 W/1 cm linear bar [8]. Because of these dramatic improvements in efficiency over flashlamp pump sources and the longer-lived and simpler operation, laser diode pump sources would be preferred for many applications. Although considerable progress has been made in the use of smaller CW-diode arrays for end-pumped laser geometries, there have been only limited efforts to use larger incoherent arrays to side pump other lasers [6], [9], [10]. The impediment is currently the high cost of these arrays. When using multiple arrays to side pump many neodymium-doped crystalline host materials with relatively narrow absorption bands, there is an additional premium to be paid for wavelength selection and therefore a host material with strong and broad absorption bands is desirable.

Some of the neodymium-doped laser glasses have such pump bands and in addition can be doped at relatively high levels without suffering substantial fluorescence quenching or loss of optical quality. In general, the stimulated emission cross section in these laser glasses is low and therefore to achieve sufficient gain with diode side pumping, the pump density must be high and this requires a strong absorption at the pump wavelength. Denker *et al.* have reported pulsed lasing in small 0.5 × 1 × 20 mm highly neodymium doped phosphate glass slabs side pumped by a series of light-emitting diodes [9]. With a neodymium concentration of 1.3×10^{21} cc^{-1}, the effective absorption coefficient for these broad-band LED pumps was 10 cm^{-1}. Reed *et al.* have recently reported experiments using a large, 4 × 10 mm pulsed laser diode array to side pump Nd:YAG and Nd:glass (LHG-5) zigzag slab oscillators [10]. They were able to achieve an optical to optical slope efficiency of 23 percent with Nd:YAG but only 13 percent with the Nd:glass slab. Much better performance has been demonstrated earlier with similar glass in the end pumped geometry [11]. In that work, 33 percent efficiency, based on pump light absorbed, was obtained with 3 percent Nd:LHG-5, a low-loss Hoya phosphate laser glass.

In this work, we have used a Hoya phosphate glass, LHG-8, doped with 6 wt. percent of Nd_2O_3 which gives an Nd^{+3} concentration of 6.2×10^{20} cm^{-3}. According to the data sheets from Hoya [12], the laser cross section σ is 4.2×10^{-20} cm^2 and the fluorescence lifetime τ is ~270 μs for this doping level compared to ~410 μs in the limit of low concentration. The loss at 1.054 μm was not measured, however the loss in their 3 percent-doped glass is 0.1 percent cm^{-1}. A small slab, 1 mm thick × 6 mm high × 20 mm long was fabricated, and the 1 × 6 mm ends were cut parallel at Brewster's angle (56°) in the plane of the large face. In this configuration the light path is straight through with no bounces and the optical aperture outside the slab is 1 × 3.9 mm. The slab was mounted over a 10 cm concave radius high reflecting mirror (760–840 nm) so that pump light from the side could pass twice through the 1 mm thickness. None of the slab surfaces were AR coated. The laser diode array pump consisted of six linear 1 cm bar arrays stacked together giving an emitting area of 1 cm × ~1.7 mm. This array was oriented parallel to the long axis of the slab and positioned within 0.5 mm of the face. The individual emitters along the bar are essentially incoherent. The output diverges at about 10° FWHM in the plane of the array and about 35° FWHM in the perpendicular plane. Inside the slab, the divergence is reduced to 23° FWHM due to the index of refraction ($n = 1.53$), and therefore the height of the pumped region is about 25 percent larger after one pass through the 1 mm thickness.

At 20°C, the spectral emission was centered at 812 nm and therefore substantial cooling was required to shift the output to more closely match the peak of the Nd:LHG-8 absorption at 802 nm. Fig. 1 shows the absorption spectrum measured on a Cary 2390 spectrophotometer and the emission spectrum of the diode arrays measured with an integrating sphere at a heat sink temperature of −14°C. From this data the attenuation of the pump intensity into the slab was calculated. The average initial absorption coefficient is greater than 16 cm^{-1} and decreases to ~15.5

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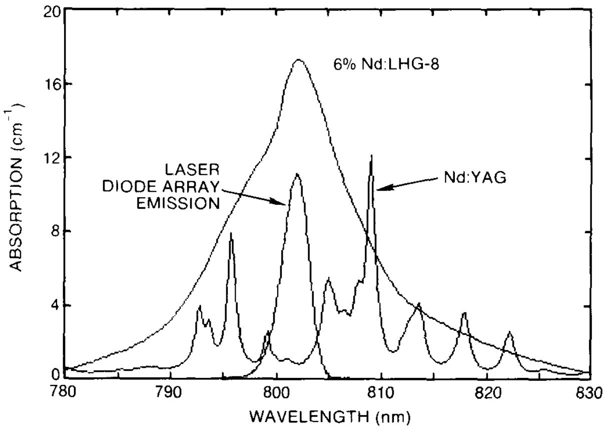

Fig. 1. Measured absorption spectrum for the 6 wt. percent Nd_2O_3-doped LHG-8 laser glass and 1 percent Nd : YAG and the emission spectrum in arbitrary units for the 6-bar diode array at a heat sink temperature of −14°C.

cm^{-1} after 2 mm. This calculation predicts that for the minimum distance, straight through path lengths, about 85 percent of the pump energy would be absorbed in 1 mm and over 95 percent absorbed after two passes. This agrees well with the measured ~18 percent single pass transmission through the slab. A similar calculation was performed for 1 percent Nd:YAG with the laser diode spectrum shifted for optimum overlap with the strongest absorption band at ~807 nm and the absorption ranged from 7 to 5.5 cm^{-1} over a 2 mm path length. Thus, with this diode array, pump energy can be deposited at 2 to 3 times the density in the 6 percent neodymium phosphate glass compared to 1 percent Nd:YAG. Clearly, a greater difference would be expected with a broader pump spectrum.

The laser experiments were performed with an optical cavity consisting of a 30 cm radius concave high reflector and various flat output couplers spaced ~7.5 cm apart, not counting the offset due to the tilted Brewster cut slab. The calculated TEM_{00} mode radius normal to the slab face is $\omega_0 = 0.22$ mm and therefore the laser was operating in only a few transverse modes at most. Optical pump pulses were 200 μs long with a nearly flat top and a rise time of about 20 μs. The temporal behavior of the pump pulse and the laser output is shown in Fig. 2. Here, the peak pump power is ~170 W and the output coupling is 5 percent. There is a turn on time of ~25 μs for laser oscillation and then a gradual rise in power with characteristic relaxation oscillations until steady-state behavior is reached for the last ~75 μs of the pulse.

The laser output at 1.054 μm was integrated with a Laser Metrics model 7200 energy meter. We measured the laser diode pump array output versus current with a calibrated integrating sphere and also with a Scientec power meter. The laser performance in terms of energy incident on the slab is shown in Fig. 3 for output mirror reflectivities of 98, 95, and 90 percent. At the maximum diode drive current corresponding to 34.5 mJ of pump energy incident on the slab face, we obtained 7.5 mJ from the glass laser using the 95 percent mirror which gives an optical to optical efficiency of 22 percent. The optical slope efficiency at high pump levels was 29 percent. These efficiencies are similar to those we obtained earlier by side pumping a polished 3 mm diameter Nd : YAG rod with a 3-bar diode array stack [6]. From the variation of pump threshold and limiting slope efficiency with mirror reflectivity, we estimate the intrinsic cavity loss to be less than 0.5 percent per pass.

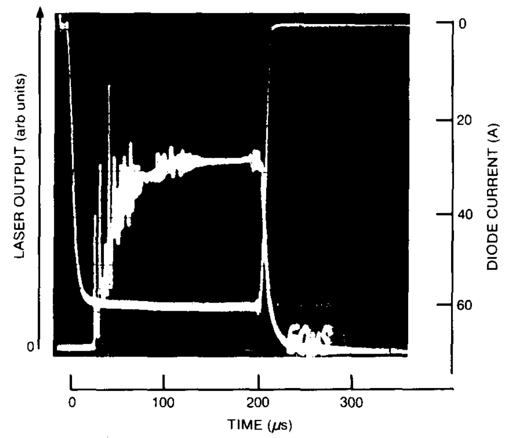

Fig. 2. Nd : LHG-8 laser output with a 95 percent reflector. The diode current pulse is 60 A giving 34.5 mJ of pump energy.

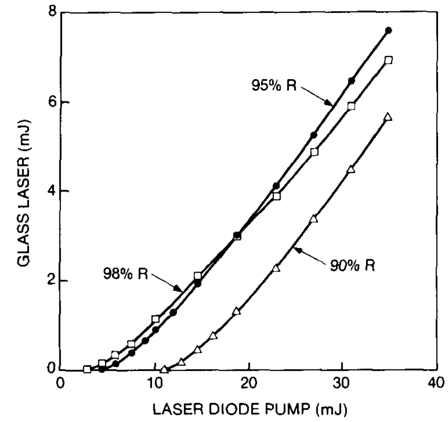

Fig. 3. Laser performance at 1.054 μm as a function of pump energy incident on the slab face for different output mirror reflectivities.

These results are significantly better than those reported earlier using a 4 × 10 mm diode array stack to side pump zig-zag glass slabs [10]. In that work, slabs of 0.7 percent Nd:YAG and 3, 6, and 8 wt. percent Nd:LHG-5 were fabricated to operate with three internal bounces and near Brewster's angle entrance. The diode array was close-coupled to the slab face normal to the plane of the light path. The emission was ~10 nm wide and centered at 807 nm. In order to match the pump absorption depth, the YAG slab was 4.6 mm thick and the glass slabs were 2 mm thick. The TEM_{00} mode radius was ~20 percent of the glass slab aperture, similar to the present case. Optical slope efficiencies of 23 percent for Nd:YAG and 6, 11, and 13 percent were reported for the glass slabs respectively. It seems likely that the relatively poor results for the low gain glass were due to poor energy extraction from the slab volume. In this zig-zag slab geometry, as opposed to a straight-through geometry employed in the present work, the laser cavity modes traverse the entire depth of the pumped region and therefore the effective single pass gain is determined by the average pump density (scaled somewhat due to the longer path lengths). At low laser intensities, the extraction from the pumped regions between the bounces is poor for low-order transverse modes. In the present work, the laser is optimized by extracting from the region near the pumped face. The peak pump density here is also roughly twice that found in the earlier work because of the larger effective absorption coefficient. At higher pump levels the slope efficiencies would presumably increase for that particular zig-zag geometry.

In summary, we have demonstrated 22 percent optical efficiency in a long pulse, multimode diode pumped laser oscillator based on a phosphate laser glass, LHG-8, highly doped with Nd_2O_3. The strong and wide absorption bands in such phosphate glasses allow efficient pumping while somewhat relaxing the expensive wavelength selection requirements for laser diode arrays compared with crystaline host materials. With such materials, smaller slab thicknesses or rod diameters than are feasible with Nd:YAG can be used in the side pumping geometry.

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