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High Power Diode-Bar-End-Pumped Nd:YLF Laser at 1.053µm

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Abstract

We describe efficient cw operation of a Nd:YLF laser on the 1.053µm transition, end-pumped by two beam-shaped 20W diode bars. Fundamental-transverse mode operation with output power of 11.1W for ~29.5W of incident pump power has been demonstrated. In Q-switched operation 8.4W of average power at a pulse repetition frequency of 40kHz and ~2.6mJ pulse energy at pulse repetition frequency of 1kHz were achieved.

Power-scaling of diode-end-pumped solid-state lasers to multiwatt (>10W) output power whilst retaining the high efficiency and diffraction-limited beam quality, that have been characteristic of operation at low powers, is attracting growing attention[1] due to the numerous potential applications of such sources. However, even with the advent of effective beamshaping schemes[2], to allow focussing of high-power diode-bar pump sources to spot-sizes suitable for efficient end-pumping, progress in power scaling of TEM_{00} operation has been hindered by the onset of strong thermal effects which result from the high thermal loading density in end-pumped lasers. To date, the avoidance of thermally induced fracture has played a key role in laser design, greatly restricting the choice of laser material to crystals, such as YAG, which have a high fracture limit. Unfortunately, however, YAG has rather poor thermo-optical properties as it exhibits significant stress-induced birefringence and highly aberrated thermal lensing. The latter is particularly pronounced in high-power end-pumped lasers, due to the high thermal loading density, leading to a significant degradation in beam quality. Various solutions to this problem have been reported, including the use of aspheric lenses to compensate for the thermally-induced aberration,[3] or face cooling of a thin disc of laser material[4] to reduce radial heat flow and hence reduce thermal lensing. However, these approaches have the disadvantage of adding further complexity to the resonator design.

An alternative strategy is to employ a laser material with good thermo-optical properties. Nd:YLF is an important material in this respect since it is naturally birefringent and exhibits weak thermal lensing on the σ-polarisation corresponding to operation at 1.053 µm. The weakness of this lensing is the result of a combination of negative lensing (itself rather weak) due to the temperature dependence of refractive index ($dn/dT = -2.0 \times 10^{-6}\ K^{-1}$) and a small positive contribution from end-face bulging which counteracts the negative lens. The net result is that the power of the thermal lens in Nd:YLF (under lasing conditions) is typically a factor of 17 smaller than in Nd:YAG under comparable pumping conditions.[5] Thus, by virtue of the reduced lensing and in particular the reduced aberrations that accompany the lensing, it should be possible to scale the TEM_{00} power from Nd:YLF to considerably higher power than is currently possible with Nd:YAG. Unfortunately, however, power-scaling with Nd:YLF has been hindered by its rather low fracture limit which is ~5 times lower than in Nd:YAG. In this paper we describe a strategy for avoiding the problems of stress-fracture in diode-end-pumped Nd:YLF and, by exploiting the weak thermal lensing for 1.053 µm, demonstrate an efficient diode-pumped Nd:YLF laser with a cw TEM_{00} output of >10W. Q-switched operation of this laser is also reported.

The strategy employed to overcome the low fracture limit was to use a long Nd:YLF crystal and distribute the pump absorption over its length either by detuning the pump wavelength from the absorption peak, or alternatively by using a YLF crystal of lower Nd concentration.[6] This implies the use of a high-power diode pump source with reasonable beam quality, so that there is minimal diffraction spreading of the pump beam over the length of the Nd:YLF rod when the pump is focussed to a small enough waist size for efficient end-pumped operation. The problem with the present generation of high power diode-bar pump sources is that they produce a highly elliptical output beam which is typically >2000 times diffraction-limited in the plane of the array making it difficult to focus to the required beam characteristics. We have therefore employed the two-mirror beam-shaping technique[2] to reconfigure the pump beam to have nearly equal M^2-values in orthogonal planes thus allowing focussing to a nearly circular beam with the required combination of small diameter and low divergence. Our experimental set up (shown in fig. 1) makes use of two 20W diode-bar pump lasers (model OPC AO20-mmm-CS), operating at 797nm, and focussed into opposite ends of the Nd:YLF rod using pump delivery schemes incorporating two-mirror beam shapers, similar to the arrangement described in ref 2. For diode-bar A the resulting $1/e^2$ waist radii were 350µm and 300µm in orthogonal planes with corresponding M^2-values of ~78 and ~60 respectively, and for diode bar B the $1/e^2$ waist radii were 325 µm and 260 µm with corresponding M^2-values of ~63 and ~70 respectively. While much smaller spot sizes are possible with the beam-shaped output, these larger spot sizes were chosen to ensure that the confocal parameter in Nd:YLF (in this case ~12mm) is significantly longer than the absorption length for the pump, ensuring negligible diffraction spreading of the pump beam over the length of the pumped region. The total transmission of the pump delivery scheme was ~75 % (with typical transmission of the fibre lens ~87%, beam shaper ~92%, lenses ~96% and dichroic mirror ~96%) resulting in a maximum combined pump power incident on the Nd:YLF rod of ~29.5 W.

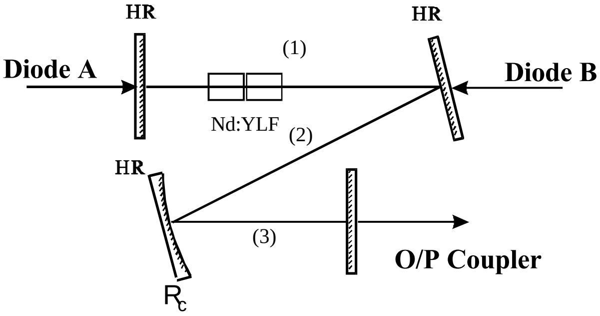

Fig. 1 Schematic Diagram of the Nd:YLF laser resonator under cw operation (HR= High Reflector, R_c= Radius of curvature = 100mm)

A simple folded resonator was employed (fig. 1) consisting of four mirrors ; two plane high reflectivity mirrors (R>99.8%) at 1.053 µm with high transmission (>95%) at the pump wavelength (~797nm), a concave high reflector and a plane output coupler. The extra fold in the cavity facilitated coupling of the two pump beams into opposite ends of the laser rod. Due to the lack of a long enough Nd:YLF rod it was necessary to use two Nd:YLF rods instead. Each rod was 8 mm long, with Nd concentration of approximately 1% and both faces were antireflection coated at the lasing wavelength. The two rods were held in water-cooled copper heat sinks, maintained at a temperature of ~15 °C and positioned very close to each other with a gap of less than 0.5mm. Both rods were oriented with their c-axis perpendicular to the pump polarisation and the resonator plane so that both diodes pumped the weaker σ-polarised transition and absorption of each pump beam took place over the length of both rods. The longitudinal distribution of the absorbed pump was further extended by slightly detuning the diode wavelength from the absorption peak at ~797nm, with the net result that ~93% of the pump light was absorbed, corresponding to an effective absorption length of ~ 6mm. This proved to be a very effective measure for reducing the risk of fracture, the two rods being operated safely at the maximum pump power.

The Nd:YLF laser was operated on the lower gain 1.053µm transition to take advantage of the weak thermal lens which has a dioptric power ~2.3 times smaller than for the polarisation corresponding to 1.047µm transition. At the maximum available pump power the thermal lens had a measured focal length of ~700mm. This relatively weak thermal lens allowed a cavity design to be constructed in which the mode sizes did not significantly change with pump power. The lengths of the arms (1), (2) and (3) were respectively 105mm, 240mm and ~50mm. The short arm was adjustable, with the output coupler mounted on a translation stage to enable the laser mode size to be varied, thus allowing excellent mode matching between the pump and the laser. A Brewster plate was also added to the resonator to ensure operation on the 1.053µm line throughout the pump power range. At full pump power the laser would, in fact, operate on the 1.053µm line without any polarisation selection but would switch to the 1.047µm line at lower pump power. The explanation for this is that the stronger lensing at 1.047µm (π-polarisation) results in the cavity becoming unstable at high pump powers for the 1.047µm transition.

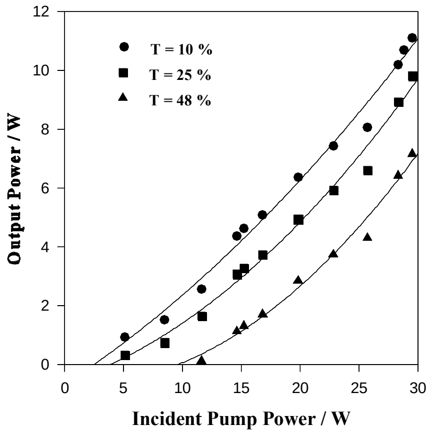

Fig. 2 Output power versus incident pump power under cw operation with output coupler T = 10 % (circles), T = 25 % (squares) and T = 48 % (triangles)

Fig. 2 shows the cw output power as a function of the incident pump power for various output couplers. At the maximum pump power (29.5W incident, 27.4W absorbed) the highest laser output power of 11.1W was achieved with an output coupler of 10%. For this output coupler the threshold pump power was relatively low at <2W. The average slope efficiency was ~40% with respect to the incident pump power. At high pump powers there was a noticeable increase in slope efficiency to ~55%. This increase was partly due to the change in steady-state temperature and hence wavelength of the diode bar, as the pump power was varied, leading to an increase in the fraction of the pump power absorbed, and also due to increased saturation of the gain in the wings of the pumped region at higher powers. The beam quality factor was measured using a Coherent

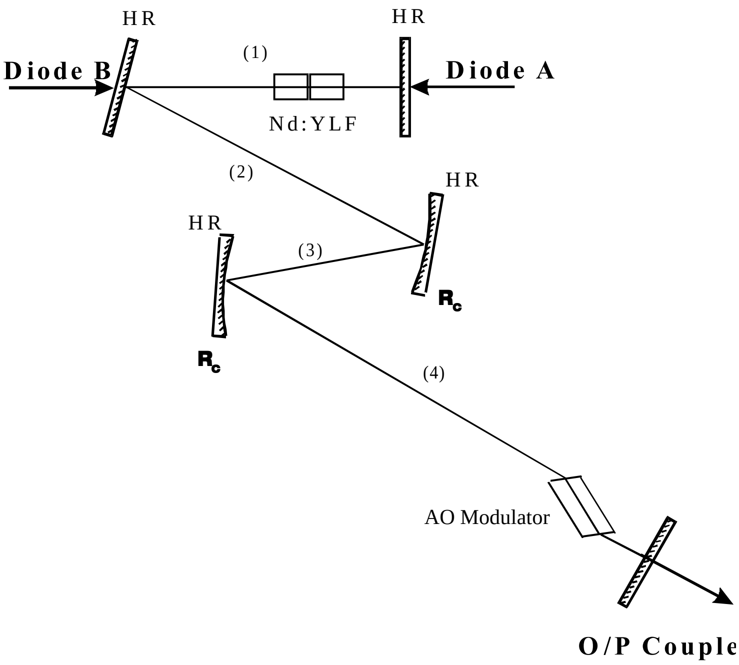

Fig.3 Schematic Diagram of the Nd:YLF laser resonator under Q-switched operation. (HR= High Reflector, R_c= Radius of curvature = 200mm)

Modemaster, which indicated M^2-values of less than 1.1 in both orthogonal planes over the entire pump power range. In addition, due to the relatively weak thermal lens, the laser output spot size varied by only 10% over the whole pump power range. This attractive feature of Nd:YLF lasers operating at 1.053µm suggests that there is considerable scope for scaling cw TEM_{00} operation to much higher powers. Q-switched operation was also investigated using a slightly modified cavity design, as shown in fig. 3. This z-fold cavity avoided having a small laser mode size at the o/p coupler, hence reducing the risk of optical damage to the dielectric coatings. The Q-switch, a 80MHz Brewster-angled TeO_2 acousto-optic modulator required a large mode size in order to avoid damage and hence was located in the longest arm of the resonator close to the output coupler. The lengths of the arms 1, 2, 3 and 4 were respectively, ~130mm, ~235mm, ~230mm and ~320mm. The separation between the two curved mirrors was adjusted to optimise the mode-matching.

The Q-switched performance was investigated as a function of repetition rate, from 1 to 40 kHz at the maximum pump power. The dependence of average power and pulse energy on the repetition rate is shown in fig. 4. At a repetition rate of 40kHz the pulses have a FWHM duration of 150ns and produce an average power of 8.4W corresponding to a pulse energy of 0.21mJ and a peak power of 1kW. At lower repetition rates the pulse energy increases and the average power decreases as expected. At a repetition rate of 1 kHz, the Nd:YLF pulses had a FWHM duration of 50ns and the average power was 2.6W, corresponding to a pulse energy of ~2.6mJ and a peak power of 50kW. Thus it can be seen that at low repetition rates the pulse energies are somewhat less (~ factor-of-two smaller) than would be expected on the basis of the cw performance and the relatively long fluorescence lifetime in Nd:YLF of ~520µs. A rough estimate of the reduction in inversion density due to ASE[7] suggests that the pulse energy would be reduced by <0.2 mJ, at repetition rates <1KHz. Hence we believe that this degradation in performance was mainly caused by a combination of the high gain in the Nd:YLF (hence fast pulse buildup-time) and the relatively slow switching speed of the A-O modulator, the latter being exacerbated by the need to place the modulator in a region of the cavity with a large spot size to avoid optical damage. Thus, with further optimisation of the cavity design to reduce the gain and by using an A-O modulator fabricated from a material with higher damage threshold (e.g. fused silica), it should be possible to achieve a significant improvement in performance at low repetition rates.

In conclusion we have described a strategy to avoid the stress fracture problems in end-pumped Nd:YLF. Using this approach we have demonstrated a reliable, highly efficient, high-power

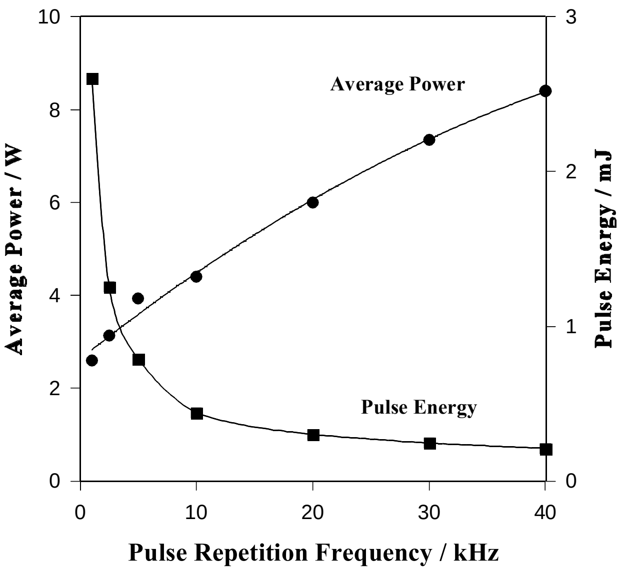

Fig. 4 Average power and Pulse Energy verses pulse repetition rate under Q-switching operation

Nd:YLF laser, at 1.053µm, with 11.1W of TEM_{00} output and excellent beam quality ($M^2 <1.1$). TEM_{00} operation with $M^2 <1.1$ was maintained throughout the pump power range with only a small variation in laser mode size. The combination of the excellent thermo-optical properties of Nd:YLF at 1.053µm and this strategy for avoiding thermally-induced stress fracture suggest that there is considerable scope for further power-scaling of end-pumped Nd:YLF lasers while maintaining TEM_{00} operation.

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