DESIGN CONSIDERATIONS FOR HIGH-POWER TEM_{00} OPERATION OF END-PUMPED SOLID-STATE LASERS

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ABSTRACT

A resonator design strategy for high-power end-pumped solid-state lasers is described, which reduces the beam distortion due to thermally-induced lens aberrations. The approach is based on a resonator design satisfying two criteria: firstly, the laser mode radius must be appreciably smaller than the pump beam radius, and secondly, the laser mode size must decrease with decreasing power (increasing focal length) of the thermal lens. Experimental results are presented for diode-bar-pumped Nd:YAG lasers confirming the validity of this approach. A simple technique, employing a single quarter-wave plate, for reducing the depolarisation loss due to thermally-induced birefringence is also described. Using this approach, the depolarisation loss for a diode-bar-pumped Nd:YAG laser operating at 946nm has been reduced from ~1.7% to <0.001%, resulting in 2.9W of linearly-polarised output for 14.3W of incident pump power.

1. INTRODUCTION

Recent advances in semiconductor laser technology have led a very significant increase in the available output power from diode-bar sources, and as a result there has been growing interest in using high-power diode-bars as pump sources for power-scaling of solid-state lasers. At relatively low pump powers (<few watt), the use of end-pumped rather than side-pumped geometries has been the preferred route owing to the much higher efficiencies achievable, the relative ease with which fundamental transverse mode operation can be selected and the enormous flexibility in cavity design and operating wavelength. Many of these attractive features stem from the relative ease with which low power diodes can be focused to small beam sizes, combined with their relatively narrow emission linewidths allowing short absorption lengths (typically ~few mm) in the laser material.

Progress in scaling diode-end-pumped solid-state lasers to high powers, whilst retaining these attractive features, has been hindered by two main problems. The first of these has been the unfriendly and highly elliptical nature of the output from high-power diode-bars, which is nearly diffraction-limited in the plane perpendicular to the array, but is typically ~2000 times diffraction-limited in the array plane. This large mismatch in the M^2 beam quality factors for orthogonal planes makes it difficult to focus to the small diameter beams required for efficient end-pumping of solid-state lasers.

To allow focusing to small beam diameters it is necessary to use a beam delivery scheme which equalises the M^2 values in orthogonal planes without significantly decreasing the brightness. Recently, a number beam delivery schemes which attempt to solve this problem have been reported (e.g. ref.1), offering the attractive prospect of efficient high-power operation even on relatively low gain or quasi-three-level transitions[2].

However, the availability of high power and high intensity pump sources has further exacerbated thermal effects such as thermal lensing and thermally-induced stress-birefringence, which are particularly pronounced in end-pumped lasers owing to the high thermal loading density. One of the main problems encountered in end-pumped lasers is beam distortion due to the highly aberrated thermal lens, making it extremely difficult to simultaneously achieve high efficiency and good beam quality. To overcome this problem a number of approaches have been reported including the use of apertures to select the

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TEM_{00} beam[3], and aspheric lenses as compensators[4]. More recently, an alternative approach has been reported[5], which uses face-cooling to achieve axial heat flow in a thin disc of laser material, and hence a significant decrease in the strength of the thermal lensing. Unfortunately, the latter approach has the disadvantage that it is only applicable to laser materials with a short absorption length for the pump light and/or laser transitions with a high gain cross-section. This is necessary to ensure that the pumped region has a high aspect ratio of pump beam size to disc thickness to minimise radial heat flow.

In this paper we describe an alternative resonator design strategy to reduce the beam distortion resulting from strong thermally-induced aberrations without using compensating components. The underlying basis of this approach is that the aberrations which result from the Gaussian-like pump beam are most pronounced in the wings of the pumped region. Hence by using a resonator with a TEM_{00} mode which is smaller than the pump beam it is possible to achieve a near-diffraction-limited output beam. However, a consequence of the smaller mode size there is unused inversion in the wings of the pumped region which may provide sufficient gain for simultaneous oscillation on higher-order transverse modes. Suppression of higher-order transverse modes can be achieved by applying a second condition to the resonator design, namely that the TEM_{00} beam size in the laser rod should decrease with increasing focal length of the thermal lens. The rationale for this design is presented below, together with experimental results for a diode-bar-pumped Nd:YAG laser which confirm the benefits of this approach. Finally, a simple technique, using a single quarter-wave plate, for reducing the depolarisation loss due to thermally-induced birefringence in resonators employing a single laser rod is also described. Results for a diode-bar-pumped Nd:YAG laser operating at 946nm which demonstrate the advantages of this approach are presented.

2. THERMAL LENSING IN END-PUMPED SOLID-STATE LASERS

In the work described here we are restricting our consideration to end-pumped lasers with side-cooled rods of cylindrical geometry. The attraction of side cooling is the relative simplicity of its implementation, but due to the predominantly radial heat flow it has the disadvantage of strong thermal lensing. One of the main problems is that the thermal lens is highly aberrated, due to the Gaussian-like intensity profile of the pump beam, leading to a very pronounced degradation in beam quality. In laser materials, such as Nd:YAG, with its high stress-fracture limit, it is generally the aberrated thermal lens which presents the most difficult obstacle to simultaneously achieving both high efficiency and a diffraction-limited TEM_{00} output in high-power end-pumped lasers.

To enable the formulation of an appropriate resonator design strategy to minimise degradation in beam quality, and hence obtain the optimum TEM_{00} performance at high pump powers, it is necessary to know the focal length of the thermal lens and determine the effect of the non-parabolic phase aberrations on beam quality. For an edge-cooled laser rod of radius a, length l mounted in a heat-sink with its outer curved surface maintained at a constant temperature and end-pumped by a diode-laser with pump intensity $I_p(r)$, the phase difference, $\Delta\phi(r)=\phi(0)-\phi(r)$, which results from thermal loading and the temperature dependence of the refractive index is given by the approximate expression[6,7]:

$$\Delta\phi(r) = -\frac{2\pi}{\lambda}\int_o^l\int_o^r \frac{h(r',z)}{K_c}.\frac{dn}{dT}\,dr'\,dz \tag{1}$$

where K_c is the thermal conductivity and h(r,z) is the heat flux (assumed to be purely radial) given by

$$h(r,z) = \frac{\alpha_p \gamma \exp(-\alpha_p z)}{r}\int_o^r r' I_p(r')\,dr' \tag{2}$$

where α_p is the absorption coefficient for the pump and γ is the fraction of absorbed pump converted to heat. If the pump beam has a uniform transverse intensity profile, then $\Delta\phi(r)\propto r^2$ and the resulting thermal lens has no phase aberration. However, in general the pump beam has a Gaussian-like intensity profile hence it is more appropriate to consider the resulting aberrated thermal lens as one whose focal length varies radially. For a thin thermal lens with radially varying phase difference $\Delta\phi(r)$ an approximate expression for the focal length $f_t(r)$ of the thermal lens is given by

$$f_t(r) \approx \frac{2\pi r}{\lambda \frac{d\Delta\phi(r)}{dr}} \tag{3}$$

Substituting equation (1) into equation (3) yields the following expression for $f_t(r)$:

$$f_t(r) = \frac{K_c r^2}{\eta_{abs} \gamma \frac{dn}{dT} \int_o^r r' I_p(r')\, dr'} \tag{4}$$

where η_{abs} is the fraction of pump light absorbed. It can be seen from the above expression that the focal length of the thermal lens at r=0 and its variation with r, and hence the phase aberration, is strongly dependent on the transverse intensity profile $I_p(r)$ of the pump beam. For a pump beam with a 'top-hat' intensity profile ($I_p=P_p/\pi w_p^2$ for $r \le w_p$ and $I_p=0$ for $r>w_p$, where P_p is the incident pump power), the focal length of the thermal lens is given by the following expression:

$$f_t(r) = \frac{2\pi K_c w_p^2}{P_p \gamma \eta_{abs} \frac{dn}{dT}} \qquad (r \le w_p)$$

$$f_t(r) = \frac{2\pi K_c r^2}{P_p \gamma \eta_{abs} \frac{dn}{dT}} \qquad (r > w_p) \tag{5}$$

and for a pump beam with a Gaussian transverse intensity profile, $I_p(r)=(2P_p/\pi w_p^2)\exp(-2r^2/w_p^2)$ the focal length is given by

$$f_t(r) = \frac{2f_{to}}{w_p^2}\left(\frac{r^2}{1-\exp(-2r^2/w_p^2)}\right) \tag{6}$$

where f_{to} is the focal length on axis at r=0, given by

$$f_{to} = \frac{\pi K_c w_p^2}{P_p \gamma \eta_{abs} \frac{dn}{dT}} \tag{7}$$

Thus from comparison of equations (5) and (6), it can be seen that for a Gaussian pump profile the thermal lensing on axis (r=0) is approximately a factor-of-two stronger than for a pump beam with a 'top-hat' intensity distribution. In addition, a Gaussian pump results in a thermal lens which is much more highly aberrated with only a small region in the centre ($r \ll w_p$) having essentially constant focal length. In contrast the 'top-hat' pump beam, produces a lens which is essentially unaberrated over the entire pumped region ($r \le w_p$). Thus, the intensity profile of the pump beam is a very important factor in determining the thermal lens power and its phase aberration.

3. MEASUREMENT OF THERMAL LENSING

In order to determine the thermal lens focal length in an actual diode-bar-pumped Nd:YAG laser we have made a measurement of the phase difference as a function transverse position using a Mach-Zehnder interferometer. The experimental set-up (shown in fig.1) consisted of an antireflection coated 10mm long Nd:YAG rod mounted in a water-cooled copper heat-sink, end-pumped by a 20W diode-bar (Opto Power Corporation OPC-AO20-mmm-CS). The diode-bar output beam was re-formatted using a two-mirror beam shaper[1], to roughly equalise the M^2 factors in orthogonal planes, and was focused with an arrangement of standard lenses similar to that described in ref.8. The resulting focused beam was nearly

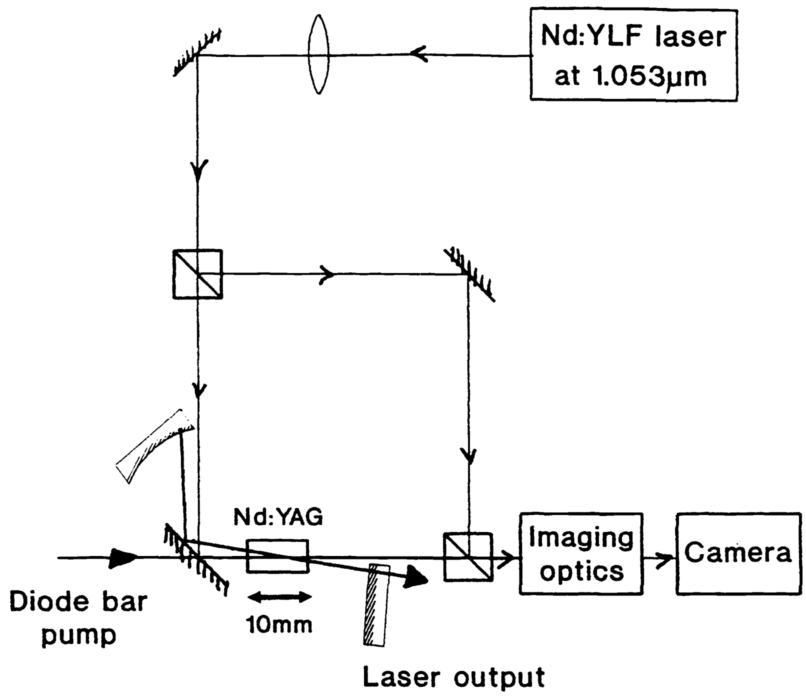

Figure 1: Mach-Zehnder interferometer for measuring the thermally-induced phase difference

circular with radii; w_{px}=227μm and w_{py}=224μm and beam quality factors; $M_x^2 \approx 78$ and $M_y^2 \approx 63$ in orthogonal planes. This choice of beam size is typical of that required for efficient operation on some of the lower gain Nd:YAG transitions (e.g. at 946nm and 1.32μm). The Mach-Zehnder interferometer arrangement used permitted measurements of the phase difference $\Delta\phi(r)$ under both non-lasing and lasing conditions. At the maximum pump power incident on the laser rod of 14.2W, the Nd:YAG laser produced ~6W of output at 1.064μm in a multi-transverse-mode beam. Under lasing conditions and at the maximum pump power the measured phase difference as a function of radial position is shown in fig.2(a). The solid line in fig.2(a) is the parabolic curve which is the best fit to the phase difference data close to the centre of the pumped region. This indicates the phase difference profile that would be measured for a perfect (unaberrated) lens, and corresponds to a focal length of ≈60mm. By comparison, the thermal lens at the centre of the pumped region, under non-lasing conditions had a focal length ~24mm - a factor-of-two shorter than the measured focal length under lasing conditions. The explanations for this difference is thought to be additional thermal loading due to upconversion effects. This clearly illustrates the importance of making thermal lens measurements under the appropriate operating conditions. The deviation of phase difference from the ideal parabolic phase difference profile, shown in fig.2(b), reveals the highly aberrated nature of the thermal lens with the phase aberration becoming increasingly pronounced for $r > w_p$. The resulting radial variation in focal length, calculated from the experimental data, is compared with predicted variation in focal length for a Gaussian pump beam given by equation (6), where it is assumed that $K_c = 13 Wm^{-1}K^{-1}$, $dn/dT = 9.86 \times 10^{-6} K^{-1}$ for YAG, $\gamma \approx 0.32$ for 1.064μm operation, w_p=235μm, and $\eta_{abs} = 0.94$ The result of this comparison are shown in fig.3, where the predicted values for focal length (dashed line) correspond to a slightly weaker lens than was measured in practice. This can be easily explained since the theoretical model does not take into account the extra contribution to lensing which arises from end-face bulging and the stress dependence of the refractive index, which are included in the experimental measurements. From independent measurements of the stress-induced birefringence, using the Mach-Zehnder interferometer, and the end-face curvature, using a Michelson interferometer, we were able to show that the relative contributions to thermal lensing are; ~86% due to temperature dependence of refractive index, ~8% due to end-face curvature and ~6% due to radial stress dependence of refractive index. Taking into account these additional contributions and simply multiplying equation (5) by 0.86 results in a predicted focal length given by the dotted line in fig.3, which is in good agreement with the experimental data.

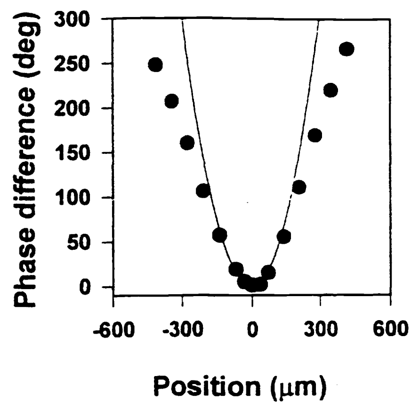

Figure 2(a): Phase difference as a function of radial position under lasing conditions.

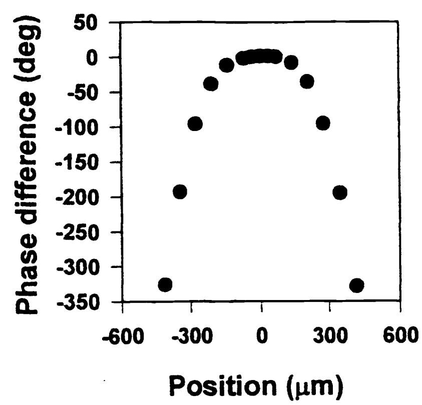

Figure 2(b): Deviation of phase difference from the ideal parabolic phase difference profile.

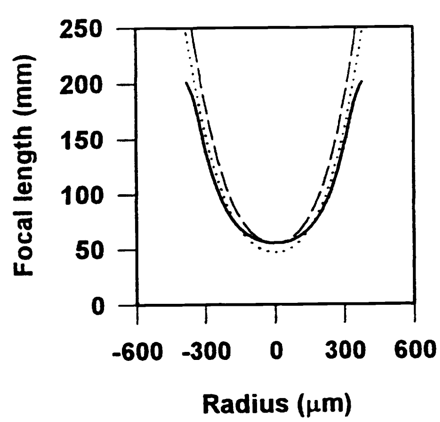

Figure 3: Radial dependence of the thermal lens focal length. (The solid line was calculated from the measured phase difference data. The dashed line represents the predicted radial dependence of focal length for a Gaussian pump beam taking into account the contribution due to the temperature dependence of refractive index only. The dotted line represents the predicted radial variation in focal length, modified to take into account the measured contributions to lensing from the stress dependence of refractive index and end-face bulging.

4. BEAM QUALITY DEGRADATION

The highly aberrated nature of the thermal lens can lead to significant beam distortion. To investigate this we have performed a simple experiment to measure the increase in M^2 for a diffraction-limited probe laser beam after a single-pass through an end-pumped Nd:YAG rod. The experimental set-up (not shown) uses the same end-pumping arrangement described in the previous section on thermal lens measurement with the probe beam, from a low-power diode-pumped Nd:YLF laser aligned to be collinear with the high-power diode-bar pump. The M^2 factor was measured using a Coherent Modemaster for a series of different probe beam sizes in the Nd:YAG rod at the maximum available pump power of 14.2W. The results, for both lasing and non-lasing conditions (fig.4) indicate a marked increase in the M^2 value and hence degradation in beam quality with probe beam size. It is also apparent that the M^2 values measured under non-lasing conditions are significantly worse than those measured under lasing conditions, implying that the thermal loading is significantly greater under non-lasing conditions. This is believed to be due to upconversion processes which lead to multiphonon decay and an increase in heat dissipation, which is especially pronounced at high inversion densities.

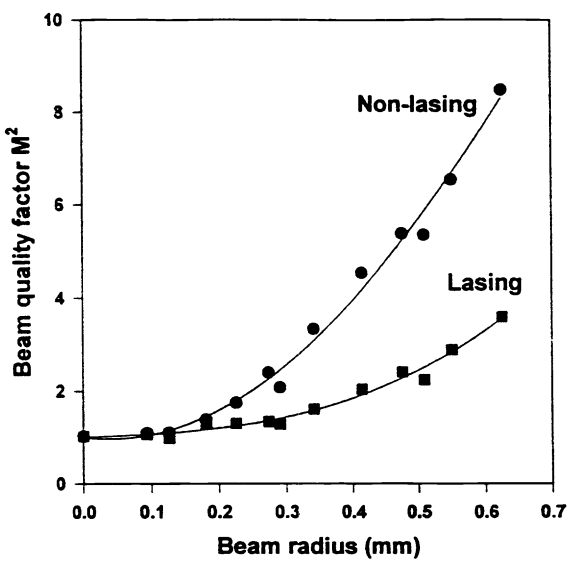

Figure 4: Single-pass degradation in beam quality versus probe beam size.

5. RESONATOR DESIGN STRATEGY

Clearly, in order to avoid significant degradation in beam quality and depolarisation loss for the TEM_{00} mode at high pump power, it is necessary to use a resonator with a TEM_{00} radius in the laser rod which is significantly smaller that the pump beam radius. This is in contrast to the situation at low powers where it is generally accepted that one should use a resonator design with $w_L \geq w_p$ for efficient TEM_{00} operation. At high pump powers, the smaller the ratio w_L/w_p the lower the depolarisation loss and the smaller the degradation in beam quality. Unfortunately one can not simply choose a resonator with an arbitrarily small laser mode size, since there will then be a significant amount of undepleted inversion in the pumped region not occupied by the laser mode, leading to multi-transverse mode oscillation and hence a non-diffraction-limited laser output. In practice therefore, it is necessary to use the largest possible laser mode size without significantly increasing the M^2 value and the depolarisation loss. The upper limit on the TEM_{00} size that can be used for laser operation with for example, $M^2<1.1$, is difficult to calculate, but a rough value can be estimated from the experimental data on single-pass beam degradation and the discussion of the preceding section. It is clear from the previous section that the laser mode must still be appreciably smaller than the pump beam to avoid significant beam distortion, hence there is still the problem of some undepleted inversion in the wings of the pumped region which can lead to lasing on higher-order transverse modes. One solution to this problem is to simply use an aperture to discriminate against the unwanted higher-order modes. However, this has the disadvantage that it can significantly increase the loss for the fundamental mode and hence be detrimental to the efficiency. An alternative approach is to make use of the radially varying focal length of the thermal lens to provide the required discrimination. This is based on the principle that higher-order transverse modes, by virtue of their larger beam size than the TEM_{00} mode, will see a thermal lens with an effective focal length which is longer than that seen by the TEM_{00} beam. Hence, choosing a resonator design where the mode size decreases with increasing focal length of the thermal lens, will effectively decrease the ratio of beam sizes of the higher-order transverse modes to the TEM_{00} mode. This results in a decrease in available gain for higher-order modes by virtue of their stronger spatial overlap with the fundamental mode, hence suppressing their oscillation.

To verify the benefits of this approach we have performed a number of experiments on a Nd:YAG laser end-pumped by a high-power diode-bar. The pumping scheme used is identical to that described in earlier sections, delivering a maximum of 14.2W in a beam of radius $w_p \approx 225\mu m$. The resonator design employed was a simple folded cavity (fig. 5), with the 10mm long Nd:YAG laser rod was mounted, as before, in a water-cooled copper heat-sink. The use of two output couplers (with transmissions of 5% and 2% at 1.064μm facilitated simultaneous monitoring of the laser output power, beam quality factor and transverse intensity profile of the output beam, whilst having the additional advantage of allowing easy determination of the laser mode size at the pump input mirror, and hence in the laser rod, without requiring a knowledge of the resonator design and the effect of the thermal lens.

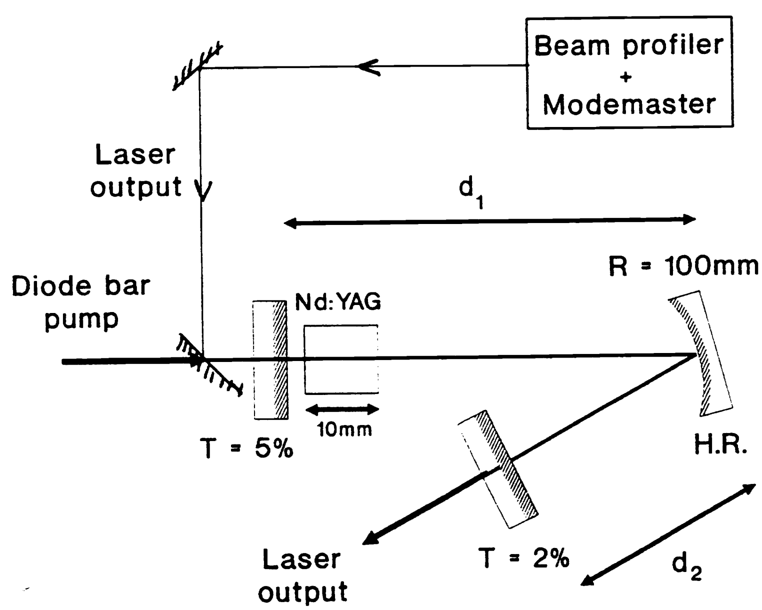

Figure 5: Resonator design for Nd:YAG laser experiments.

Using the standard ABCD matrix formalism it can be shown that a decrease in laser mode size in the rod with increasing focal length of the thermal lens can be realised by choosing an effective optical length for arm 1 to be just less than the sum of the focal lengths of the curved high reflector and the thermal lens focal length (~60mm at the maximum pump power). In our experiment the length d_1 was set to 109mm with the angle of incidence on the curved mirror made small (<5°) to render the effects of astigmatism negligible. The required TEM_{00} size in the laser rod can be obtained by simply adjusting the arm length d_2. Calculated values for the TEM_{00} beam radius at the laser rod are plotted as a function of thermal lens focal length for different values of d_2 in fig.6. Without a polariser present in the cavity and at the maximum available pump power of 14.2W, it was found that TEM_{00} operation ($M^2 \leq 1.1$) could be achieved for a small range of values d_2 of approximately (70±0.5)mm, resulting in a maximum output power of 6.2W (fig.7). Inserting a Brewster-angled plate into the cavity resulted in a linearly polarised, TEM_{00} output ($M^2 < 1.1$) of slightly lower output power 5.5W, the reduction caused

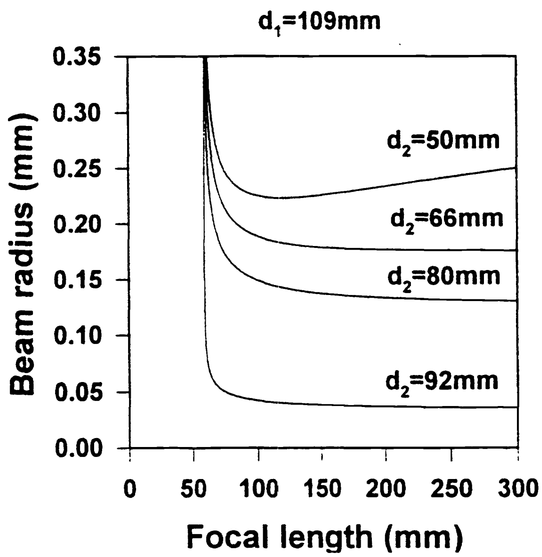

Figure 6: TEM_{00} radius versus thermal lens focal length.

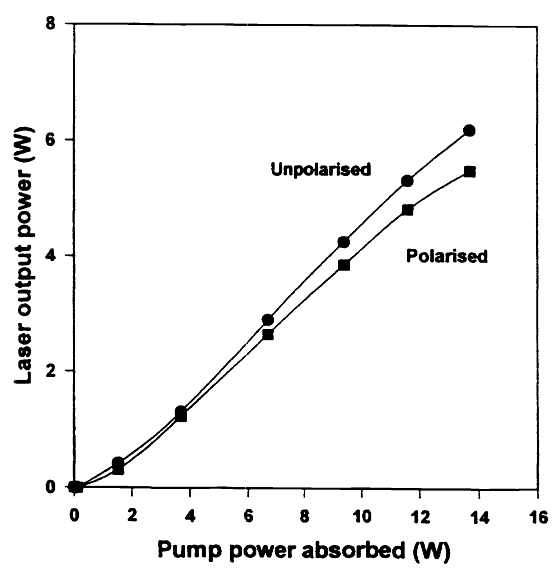

Figure 7: Nd:YAG output power at 1.064μm versus absorbed pump power.

by an additional cavity loss of ~1% due to thermally-induced stress birefringence. One interesting observation was that the reliability of TEM_{00} operation was improved as a result of including a polariser in the cavity and additionally, had the benefit of extending the range of arm lengths d_2, and hence the range of laser mode sizes, over which near diffraction-limited operation can be maintained. This can be attributed to the additional transverse mode discrimination provided by the polariser by virtue of the fact that higher-order transverse modes with larger beam sizes see, on average, a larger stress-induced birefringence and hence experience increased depolarisation loss at the polariser compared to the smaller fundamental mode.

To provide additional confirmation of the benefits of this resonator design approach, and in particular, to demonstrate the importance of using a resonator with a laser mode size which decreases with increasing thermal lens focal length, we have also investigated the behaviour of a similar folded cavity, but this time with arm lengths d_1 and d_2 selected to give a laser mode radius similar to that used in the previous experiment (i.e. ~165μm), but one which does not vary appreciably with rod focal length. At the maximum pump power, a folded cavity with $d_1 \approx 80$mm and $d_2 \approx 50$mm roughly satisfies these requirements. The minimum M^2 beam quality factor attainable for this resonator was >2, thus serving to illustrate the importance of using a resonator which satisfies both of our design criteria.

This design strategy has been successfully applied to other diode-bar-end-pumped Nd:YAG lasers operating on lower gain transitions at 946nm[2] and at 1.3μm, yielding diffraction-limited performance up to power levels of 3.1W and 3.2W respectively. However, due to their relatively low gain, both of these lasers when operated with Brewster plate polarisers, provided significantly lower powers due to the depolarisation loss resulting from thermally-induced birefringence. In the case of the 946nm Nd:YAG laser a maximum polarised output of 2.1W, and for 1.3μm operation, a maximum linearly polarised output of ~1.75W were achieved. In the latter case the much higher heat loading density, which results from the larger quantum defect, makes it more difficult to achieve an efficient, linearly polarised TEM_{00} output.

6. SIMPLE TECHNIQUE FOR COMPENSATION OF THERMALLY-INDUCED BIREFRINGENCE

For applications such as nonlinear frequency conversion, requiring a linearly polarised output, the most serious problem is often the depolarisation loss resulting from stress-induced birefringence which dramatically reduces the efficiency of low gain lasers at high pump powers. Various techniques for compensating stress-induced birefringence have been described[9,10], but which are not well-suited for low gain end-pumped lasers employing a single laser rod.

In this section, we describe an alternative technique for reducing the depolarisation loss due to stress-induced birefringence, which is well-suited for use in end-pumped solid-state lasers. The benefits of this approach have been investigated for a diode-bar-end-pumped Nd:YAG laser operating on the low gain transition at 946nm. Our approach employs only a single quarter-wave plate located in the small gap between the pump incoupling mirror and the Nd:YAG rod shown in fig.8. The quarter-wave plate is aligned with its fast or slow axis parallel to the desired plane of polarisation, in this case defined by a Brewster-angled plate polariser as the x-direction. The principle of operation can be explained by considering the transit of linearly-polarised light from the polariser to the pump incoupling mirror and back to the polariser. Rays which propagate along the laser rod in the x-z or y-z planes will not experience any change in polarisation state after a double-pass of the Nd:YAG and quarter-wave plate, since the radial and tangential components of stress are parallel or perpendicular to the x,y axes for these rays. The rays which would normally experience the largest change in polarisation state, and hence loss at the polariser, propagate along planes inclined 45° to the x-z and y-z planes, where the radial and tangential stress components are inclined at 45° to the x,y axes. With the quarter-wave plate present in the cavity, the radial and tangential polarisation components, after a single-pass of the laser rod, will subsequently be rotated by 90° on double-passing the quarter-wave plate, thus emerging after a second transit of the laser rod, with no net change in the polarisation state, and hence experience negligible loss at the polariser. Some degree of birefringence compensation will also occur for rays propagating along other sectors of the laser rod, with the net overall result that depolarisation loss is substantially reduced.

To demonstrate the effectiveness of this technique we have compared the performances of our diode-bar-pumped 946nm Nd:YAG laser with and without the quarter-wave plate present in the cavity. The results shown in fig.9 indicate that the maximum linearly-polarised output (without the quarter-wave plate) was limited by the effects of thermally-induced

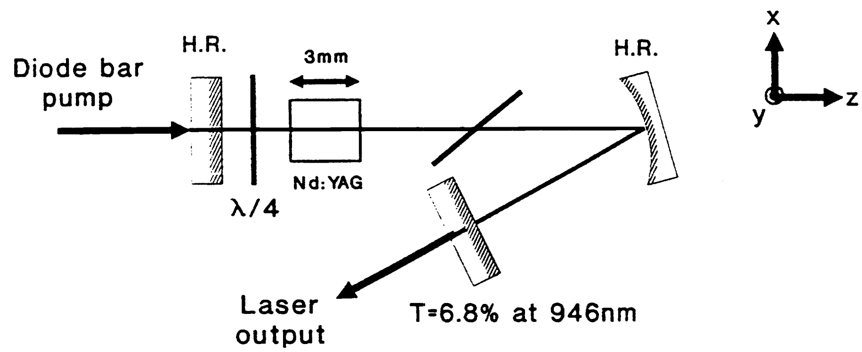

Figure 8: Diode-pumped Nd:YAG laser with a quarter-wave plate for compensating stress-induced birefringence.

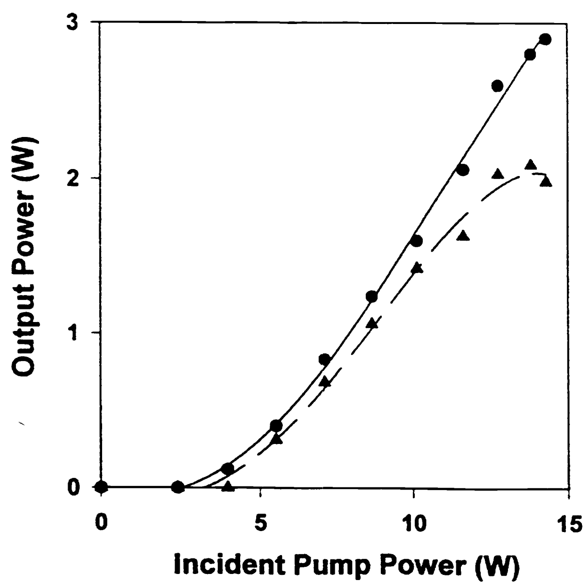

Figure 9: Laser output power versus incident pump power with the quarter-wave plate (solid-line) and without the quarter-wave plate (dotted line).

birefringence to ~2.1W. In contrast, with the quarter-wave plate present, the maximum output power was ~2.9W, limited only by the maximum available pump power of 14.3W incident on the laser rod. The output beam was also nearly diffraction-limited with $M^2<1.2$. A measurement of the power reflected from the Brewster-angled polariser plate indicated that the contribution to cavity loss arising from stress-induced birefringence was <0.001%, compared with a depolarisation loss of ~1.7% for the laser without the quarter-wave plate. These results clearly demonstrate the potential of this simple technique for compensation of thermally-induced birefringence, which should now allow further power-scaling of a various end-pumped lasers with linearly polarised output beams.

7. CONCLUSIONS

An alternative resonator design strategy has been described, which reduces the degradation in beam quality arising from thermally-induced lens aberrations in high-power end-pumped lasers. The design strategy is based on the resonator satisfying two requirements which are namely; that the TEM_{00} mode size must be significantly smaller than the pump beam size and that the TEM_{00} size must decrease with increasing thermal lens focal length. Using this approach Nd:YAG lasers, end-pumped by a 20W diode bar, have been operated efficiently with multiwatt output powers and near-diffraction-limited beam quality at 1.064μm, 946nm and 1.3μm. In addition, a simple technique for reducing the depolarisation loss due to thermally-induced birefringence has also been described, which is suitable for use in low gain and quasi-three-level end-pumped lasers. The combination of this resonator design strategy and technique for compensating thermally-induced birefringence should facilitate further brightness scaling of end-pumped solid-state lasers with a linearly-polarised output.

8. ACKNOWLEDGEMENTS

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