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Efficient high-power Tm:YAG laser at 2μm, end-pumped by a diode-bar

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ABSTRACT

Efficient, room-temperature operation of a Tm:YAG laser, end-pumped by the re-shaped output beam from a 20W diode-bar, is reported. At a rod mount temperature of 20°C and with 13.5W of diode pump power incident on the Tm:YAG rod we obtained 4.1W of output at 2.013μm in a near-diffraction-limited beam with corresponding M^2 values in orthogonal planes of 1.4 and 1.2. The prospects for further power-scaling are discussed.

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1. Introduction

Diode-pumped Tm-doped solid-state lasers operating in the eyesafe 2μm spectral region have received growing interest over recent years [1,2], due to their numerous applications in important areas such as ; medicine, laser radar and remote sensing. For many of these applications, the requirement for high average powers has restricted the scope for choice in laser material to crystals such as Tm:YAG, which have good thermo-mechanical properties and hence a high fracture limit. In common with many other Tm-doped crystals, Tm:YAG has the attraction of a quantum efficiency of ~2, when it is doped with sufficiently high concentrations of Tm^{3+} (typically at least ~3% at.), due to efficient cross-relaxation with neighbouring Tm^{3+} ions, which results in two excited Tm^{3+} ions for each absorbed pump photon [3]. This leads to the prospect of very high lasing efficiencies (comparable to those achievable in diode-pumped Nd:YAG lasers), and also implies significantly reduced thermal loading (compared to the situation without cross-relaxation), which is vitally important for high-power operation. In addition, Tm:YAG also benefits from a long fluorescence lifetime τ_f~11ms [4], which is attractive for high energy Q-switched operation. Unfortunately, due to the quasi-three-level nature and relatively low value for $\sigma\tau_f$ in Tm:YAG (~3 times smaller than for 1.064μm transition in Nd:YAG), scaling efficient end-pumped lasers to high average powers, whilst maintaining good beam quality, has proved very difficult. The main problem is the poor beam quality with highly elongated shape, provided by commercially available high-power diode-bars, which renders them difficult to focus to the intense circular beams required for efficient end-pumping of low gain quasi-three-level lasers. To lessen the demands placed on pump beam quality it has been standard practice to cool the Tm:YAG rod to reduce the re-absorption loss [1,5,6], in some cases to temperatures as low as −40°C. This has allowed limited power-scaling using polarisation-coupled broad-area diode-laser pump sources, but at the expense of significant added complexity.

In this paper we report efficient, multiwatt operation of a Tm:YAG laser at room temperature by longitudinally pumping with the re-shaped output of a single 20W diode-bar. The pumping scheme, a very important element in this work, is similar to the arrangement described in [7], incorporating a two-mirror beam shaper to re-configure the output from a conventional 20W cw diode-bar. The two-mirror beam shaper allows the highly elliptical diode-bar output beam with beam quality factors; $M_x^2 \sim 2000$ (parallel to the plane of the array) and $M_y^2 \sim 1$ (in the orthogonal plane) to be re-formatted with nearly equal beam quality factors in orthogonal planes without significantly reducing the brightness. In an optimised arrangement and depending on the initial beam quality factors, M_x^2 and M_y^2 for the diode-bar, it is possible to achieve, after re-shaping, values for M_x^2 and M_y^2 as low as 40 to 50, with the range 60 to 100 being more typical. This diode-bar end-pumping configuration has already been successfully applied to low gain transitions at 946nm [8] and 1123nm [9] in Nd:YAG yielding multiwatt laser performance. The same basic strategy has been adopted for achieving efficient, multiwatt operation of Tm:YAG at ~2μm.

2. Experiment

The pumping scheme, shown in fig. 1, is similar to that described in [7], but with the 20W diode-bar (Opto Power Corporation OPC-AO20-mmm-CS) selected for temperature tuning to the absorption peak at 785nm in Tm:YAG. The re-shaped output beam emerging from the two-mirror beam shaper was focussed with an arrangement of crossed cylindrical lenses of focal lengths, two 50mm for the plane (x-z) parallel to the array, and 75mm for the orthogonal (y-z) plane. The resulting focussed beam was nearly circular in cross-section with beam radii ($1/e^2$ intensity radius), 172μm W_x and 179μm W_y, and beam quality factors, $M_x^2 \approx 99$ and $M_y^2 \approx 97$, in the x-z and y-z planes respectively. The maximum pump power available at the focus was 15W.

With this choice of focussed pump beam size the confocal distance ($2\pi W^2 n/M^2\lambda_p$, where n is the refractive index) inside the Tm:YAG, calculated to be ~4.5mm, was more than twice the effective pump absorption length of ~2mm for the pump thereby ensuring a good spatial overlap with the laser mode and a low threshold. The Tm:YAG resonator design employed, shown in fig.2, was a simple two-mirror cavity consisting of a convex input mirror with high reflectivity (>99.8%) at the lasing wavelength (2.013μm) and high transmission (~90%) at the diode pump wavelength, a Tm:YAG rod with both end faces antireflection coated at the lasing wavelength and coated for high transmission (~93%) at the pump wavelength. The concave output coupler had a transmission ~3% at the lasing wavelength and a radius of curvature of 50mm. The 7(at)% doping level in the 8mm long Tm:YAG rod sufficient to promote efficient cross-relaxation and ensure that a large fraction (>98%) of the pump was absorbed. To allow efficient heat removal the laser rod was mounted in a water-cooled copper heat-sink maintained at a temperature of 20°C and positioned ~5.5mm from the pump input mirror. The radius of curvature of the convex input mirror was selected as -150mm to provide partial compensation of the thermal lens in the laser rod, which was estimated to have a focal length of 48mm at the maximum available pump power [10]. Both curved mirrors were mounted on translation stages to allow fine adjustment of their positions with respect to the Tm:YAG rod, this being necessary to achieve the appropriate mode-matching condition for optimum beam quality. With this arrangement, and using a total cavity length of approximately 32mm, the resonator was stable over the entire range of pump power, with the TEM_{00} beam radius in the Tm:YAG rod calculated to be 127μm at very low pump powers (<1W), increasing slightly with increasing pump power to 130μm at the maximum pump power. The TEM_{00} beam size was deliberately chosen to be smaller than the pump beam size in order to minimise the beam distortion and diffraction loss due to the highly aberrated nature of the thermal lens in end-pumped lasers [10].

For a four-level laser this leads to the problem of unused gain in the wings of the pumped region which may be accessed by higher-order transverse modes thus leading to multimode operation. To avoid this problem it is usually necessary in a four level laser to adopt further measures (e.g. using an aperture or a special resonator design [10]) to suppress oscillation on higher-order transverse modes. However, in Tm:YAG this gain is to a large extent offset by the re-absorption loss due to the quasi-three-level nature of the laser transition. This loss is especially pronounced in the wings of the pumped region, hence it helps to suppress higher-order transverse modes without the need of apertures, or special resonator designs.

3. Results and discussion

Using this resonator design and with the maximum available pump power of 13.5W incident on the Tm:YAG laser, we have achieved 4.1W of output at 2.013μm in a near-diffraction-limited beam, with M^2 beam propagation factors in orthogonal planes, measured using a Merchantek beam profiler, of 1.37 and 1.17. The small difference in the M^2 values for orthogonal planes is thought to be due in part to the slightly astigmatic thermal lensing, itself a consequence of the small mismatch in the pump beam sizes in orthogonal planes. From fig.3 it can be seen that the laser output power is essentially linear with respect to incident pump power up to the highest power level with a slope of ~34%. Thus for the laser configuration used in our experiments, the maximum 2μm power appears to be limited mainly by the available pump power, rather than by thermal effects. This suggests that there may be considerable scope for further power-scaling by simply increasing the pump power, e.g. by improving the transmission of the pump optics or using multiple diode-bars (e.g. by polarisation coupling the output from two bars). The relatively low threshold pump power of ~1.2W for room temperature operation (fig.3), compared to the available pump power, is an essential feature of the laser design for efficient operation of quasi-three-level lasers. This was made possible in these experiments by the two mirror beam shaping technique which allowed focussing of the pump beam to a small size. Another attraction of this intense end-pumping scheme for quasi-three-level lasers is that the laser performance is not strongly affected by the operating temperature, in contrast to the situation in many quasi-three-level laser configurations [5]. In fact, lowering the temperature of the heat-sink, and hence the rod temperature, by 10K produced no measurable change in the maximum laser output power.

The low threshold for this laser might at first sight, appear to suggest that further improvement in the laser output power, and hence efficiency, could be achieved using the same cavity design but with an output coupler of higher transmission (~6% say) at 2.0μm. However, under these operating conditions the maximum output power (~2.5W at room temperature) was significantly lower than with the 3% transmitting output coupler. This behaviour is thought to be the result of higher upconversion losses [5], and hence greater thermal loading, associated with the higher inversion densities required for operation with the 6% transmitting output coupler, and exacerbated by the high Tm^{3+} concentration. Thus one strategy to aid further power-scaling would be to reduce the upconversion loss by using a YAG rod with lower Tm^{3+} concentration. The lower limit on the Tm^{3+} concentration (~3% at.) would be determined by the requirement for efficient cross-relaxation. This approach would however place yet more stringent demands on the pump beam quality since it would be necessary to use a longer Tm:YAG rod to ensure that a sufficiently high fraction of the pump is absorbed. Thus, while the results reported here indicate the benefit conferred by improved pump beam parameters, it is also clear that further benefits are still to be gained by further pump beam improvements.

4. Summary

In conclusion, we have demonstrated efficient room-temperature operation of a Tm:YAG laser end-pumped by the re-shaped output from a diode-bar. For 13.5W of incident pump power at 785nm we obtained ~4.1W of output at 2.013μm in a near-diffraction-limited beam with M^2 values in orthogonal planes of 1.2 and 1.4. This compact source should find applications in a number areas (e.g. laser radar) which require a multiwatt laser operating in the eyesafe spectral region.

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5. References

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Figure Captions

Fig 1. Diode-bar focussing arrangement. Lens focal lengths are f_A = 25mm, f_B = 40mm, f_C = 63mm, f_D = 75mm, f_E = 50mm and f_F =50mm with lenses B & D focussing the y-direction. At focus, w_X=172 μm , w_Y=179 μm.

Fig 2. Tm:YAG resonator design (HR = High Reflector, Rc=Radius of curvature of mirror).

Fig.3 Output power versus pump power incident on laser rod.

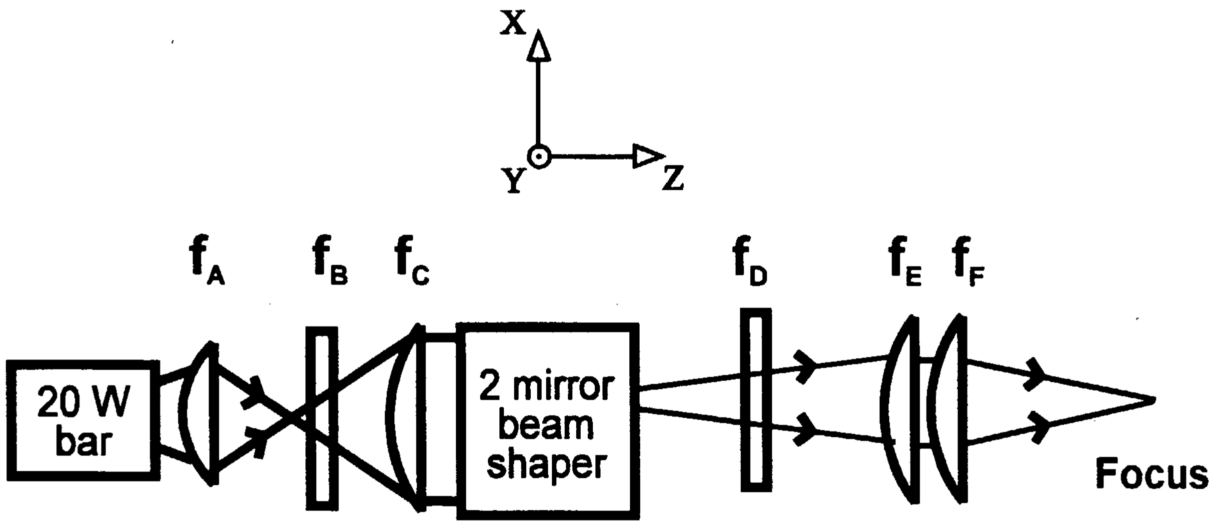

Fig.1

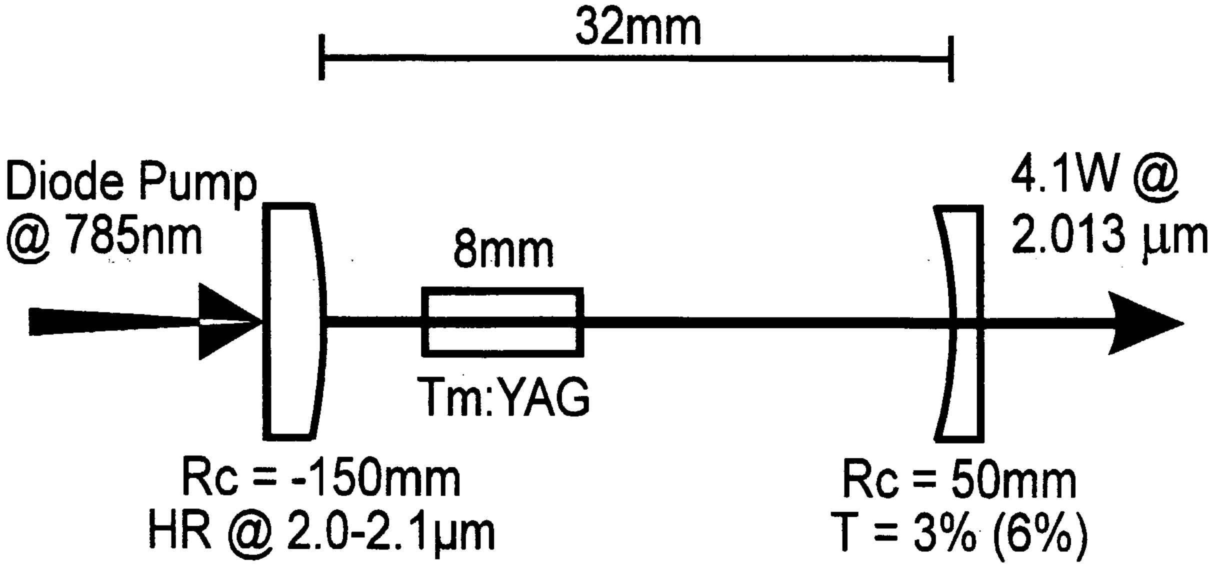
32mm
Diode Pump
@ 785nm
8mm
Tm:YAG
4.1W @
2.013 µm
Rc = -150mm
HR @ 2.0-2.1µm
Rc = 50mm
T = 3% (6%)

Fig.2

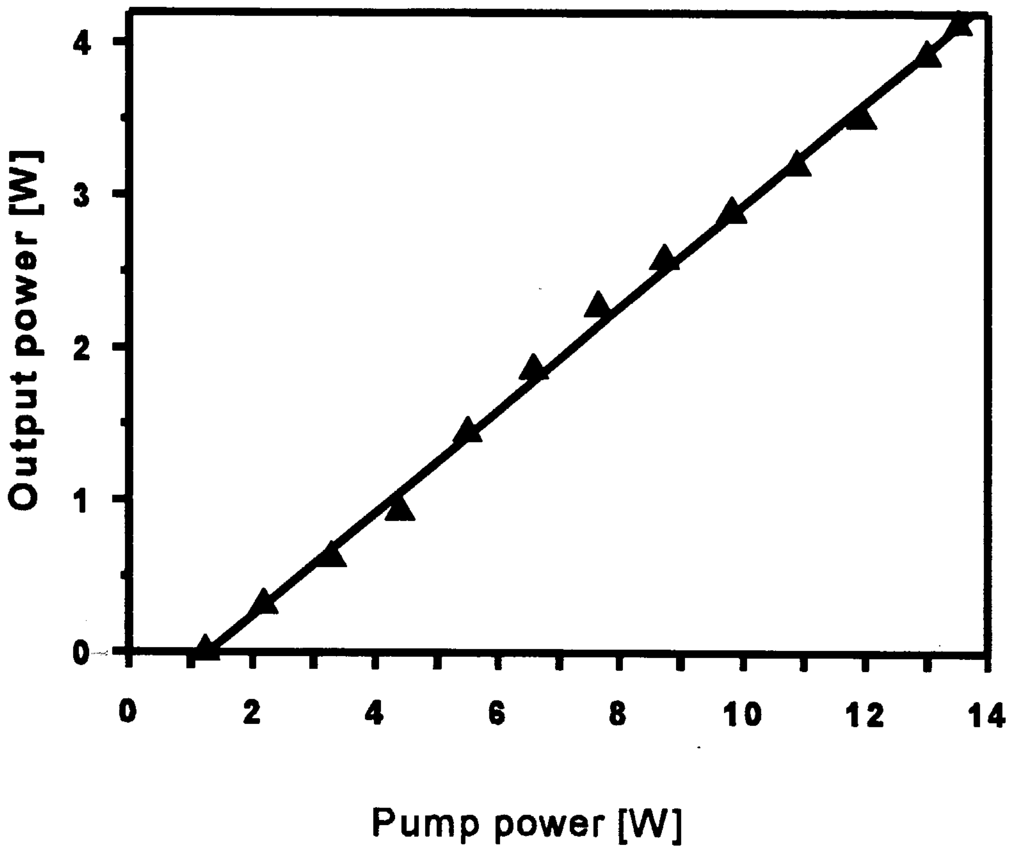

Fig.3