Opt. Comm 2594

A Diode-Bar Side-Pumped Waveguide Laser with an Extended Stable Cavity for Spatial Mode Control

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Abstract

We describe the use of an extended stable cavity to control the output spatial mode of a diode-bar side-pumped slab waveguide laser. The active medium consists of a Nd:YAG core with a one-dimensional double-clad guiding structure. The device gives >10W output power with a 56% slope efficiency for multi-mode operation, which is reduced to 33% for the best output beam quality parameters (M^2 values) of 2.8 by 1.1. The prospects for obtaining higher efficiencies and scaling to larger average powers are discussed.

Rare-earth-doped slab waveguides offer a combination of features that make them attractive for use as the active medium in high-average-power diode-pumped lasers. These include excellent thermal management and a geometric compatibility with the asymmetric output of high-power diode pump lasers [1], as well as the normal waveguide advantages of high gain and hence low threshold. In the guided axis, although multi-mode waveguides are generally required to confine the non-diffraction-limited output of high-power diode pump sources, it is relatively easy to enforce single-mode operation, for instance through the use of double-clad structures [2,3] or multi-mode interference [4,5]. However, for power-scalable side-pumping arrangements, the pumped mode size in the non-guided axis tends to be ≥0.5cm and so a short (~1cm) monolithic plane/plane cavity leads to highly non-diffraction-limited output. Extended unstable cavity designs have been demonstrated to overcome this problem and output powers of over 100W have been obtained with M^2 values as low as 1.8 by 1.1 [6]. Here we report the use of an extended stable cavity in combination with a double-clad waveguide to achieve the same goal, comparing its performance to the multi-mode case, and finding the limits to the achievable beam quality. We also discuss the prospects for improving the efficiency of the high brightness output and for power scaling.

The waveguide used in these experiments was fabricated by Onyx Optics Inc. and consisted of a 30μm-deep YAG core, of which only the central 20μm is doped with Nd (1at.%), capped by sapphire substrate and cladding layers. The waveguide was 1cm-long in the lasing axis by 5mm-wide in the pumping axis. Fig. 1 shows the experimental arrangement for side-pumping the double-clad Nd:YAG waveguide. In the guided axis, focussing of the collimated output of the fibre-lensed diode bar is achieved using a 1mm focal length, graded index lens from Doric Lenses Inc.. In the non-guided axis a 19mm focal length cylindrical lens focuses the beam through a 5mm-wide aperture, such that it is less than 1cm wide at the input side-face of the guide. Focussing through the aperture helps to break the symmetry of the pumping scheme and thus minimises the coupling of unabsorbed pump light from one diode into the other. It should be noted that it is also possible to simply proximity-couple diode bars to this type of high numerical aperture (NA) waveguide [1, 2]. The pump-coupling optics used in this case led to approximately 50% of the light being absorbed, which we attribute to the waveguide being approximately one absorption length wide for the diode bar (accounting for the double-clad structure) and a launch efficiency into the guide of nearly 80%. Consequently we were able to operate at up to 25W of absorbed pump power.

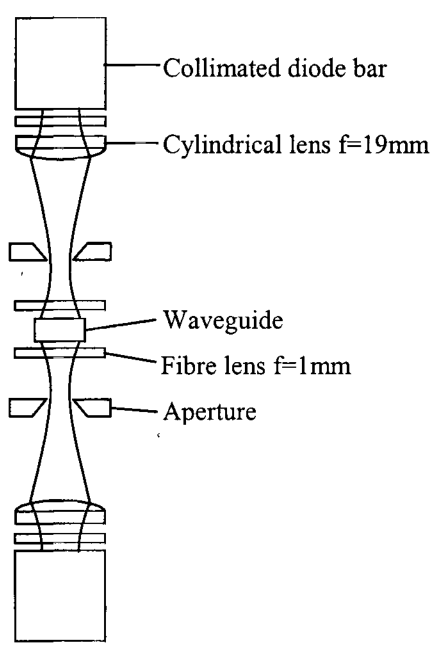

Fig. 1 Coupling optics for side-pumping.

The laser cavity, shown in Fig. 2, was designed using an ABCD matrix model. In the guided axis, fundamental-mode operation is assured by the double-clad structure and re-imaging about a plane mirror at the AR-coated waveguide intra-cavity face. This is achieved by collimating the waveguide output with a 12.7mm focal length cylindrical lens. Conversely, for the non-guided axis, a 100mm focal length cylindrical lens forms a tightly focussed beam-waist at the external plane mirror and can be tailored such that a large cavity mode fills the 5mm-wide gain region by extending the cavity length (~12cm) near to the stability limit at. The outside end-face of the waveguide was directly coated to complete the laser resonator.

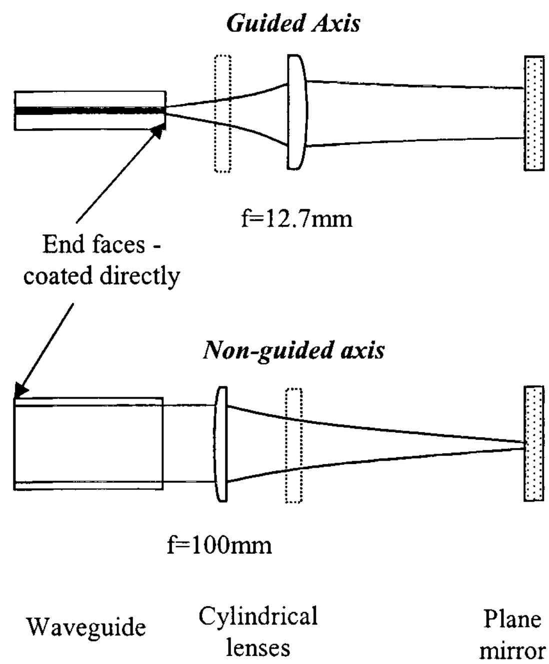

Fig. 2 Extended cavity resonator design.

Fig. 3 shows how the resulting waveguide laser output M^2 values, measured using a Coherent Modemaster M^2 meter, change with cavity length for a cavity output coupling of 19%. It can be seen that the guided axis remains diffraction-limited in all cases ($M^2<1.2$), while the beam quality in the non-guided axis reaches $M^2=2.8$ at its optimum. At this point the output beam profile appears approximately Gaussian in both axes. The use of a plane external mirror means that waists are formed in both axes at this mirror and a single cylindrical collimating lens can be used after the waveguide laser to circularise output as shown in the inset to Fig. 3.

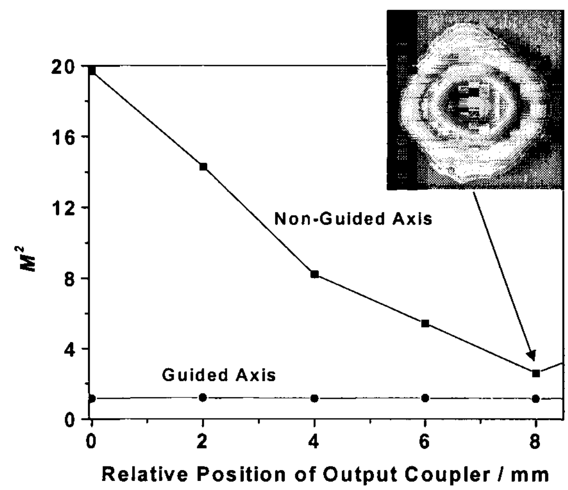

Fig. 3 Output beam quality factor against relative position of the output coupler, with T=19% and an optimum cavity length of ~12cm. The inset shows the optimised collimated output captured on a CCD camera.

Using the optimum output coupling, T=30%, for the high brightness configuration, but optimising the cavity length for power rather than beam quality, gave M^2 values as high as ~60 in the non-guided axis. Fig. 4 compares the output power performance of this highly multi-mode cavity with that of the high-brightness cavity. It can be seen that the slope efficiency is reduced from around 56% to 33% in order to achieve high-brightness output. This is due to the fact that the mode becomes near-Gaussian in the non-guided axis, giving a worse spatial overlap with the step-like gain profile. Thus the gain at the edges of the waveguide cannot be effectively used by the fundamental mode, which reduces the output efficiency and allows gain for higher-order modes such that the measured M^2 is higher than 1 in this axis.

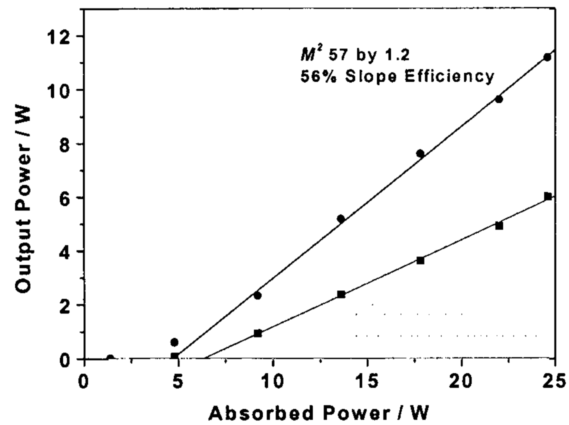

Fig. 4 Output power against absorbed pump power for the high-brightness and multi-mode cavities and an output coupling of T=30%.

The slope efficiency with respect to absorbed pump power for a 4-level laser with a unity pumping quantum efficiency is given by [7]

$$\eta = \frac{T}{(T+L)} \frac{\lambda_p}{\lambda_l} \eta_{pl} \quad ,$$

where T is the output coupler transmission, L represents the other round-trip losses, λ_p and λ_l are the pump and laser frequencies, and η_{pl} is a measure of the overlap of the normalised pump, $r_0(x,y,z)$, and laser, $s_0(x,y,z)$, spatial distributions given by [7]

$$\eta_{pl} = \frac{\left[\int_{cavity} r_0(x,y,z) s_0(x,y,z) dV \right]^2}{\int_{cavity} r_o(x,y,z) s_0^2(x,y,z) dV} \quad .$$

It is assumed that the normalised functions which represent the experimental set-up are a uniformly pumped doped core, given by

$$r_0(x,y,z) = \frac{1}{dwl}, \; for \; |x| \le \frac{w}{2}, |y| \le \frac{d}{2}, 0 \le z \le l \quad ,$$

and a laser mode with an elliptical Gaussian distribution with beam waists, ω_x and ω_y, averaged over the waveguide length, l, in the non-guided and guided axes respectively; that is

$$s_0(x,y,z) = \frac{2}{\pi\omega_x\omega_y l}\exp\left(-2\left(\frac{x^2}{\omega_x^2}+\frac{y^2}{\omega_y^2}\right)\right) .$$

Therefore, in the guided axis, lasing on the fundamental mode is expected with the beam waist equal to half the active core depth, i.e. $\omega_x = d/2$. This assumes that the mode is well confined within the full 30μm-depth of the YAG layers. If we also assume that the full width of the fundamental cavity mode in the non-guided axis is matched to the width, w, of the waveguide, i.e. $\omega_y \approx w/3$, then we find that $\eta_{pl}=0.48$. Hence the maximum possible slope efficiency for Nd:YAG operating at 1.064μm with a 807nm pump, corresponding to negligible round trip losses, is 36%, in good agreement with our experimental value of 33%. In order to improve the output efficiency of the high-brightness side-pumped waveguide laser, a zigzag lasing path could be used in the non-guided axis [8], perhaps involving a bounce off the side-walls [9], to further optimise the overlap of the lasing mode and the pumped volume.

Optimising the output coupling and cavity length for output power, a maximum of 12.2W was observed with T=42%. However, it was also noted that with this output coupling and with the cavity length set to obtain high-brightness operation, the beam quality in the non-guided axis became significantly degraded at higher pump powers with M^2 values of >6. It thus appears that the lower reflectivity cavity has a weaker control of the resonating spatial mode of the cavity and a tendency to go towards the multi-mode output of the monolithic waveguide.

The prospects for power scaling of the high-brightness, side-pumped waveguide laser appear to be good. Firstly, a similar pumping arrangement and waveguide structure would also be compatible with the use of diode-stack pumping. The 30μm-deep, 0.46-NA guides used here are compatible with the use of 3-bar stacks (available with M^2 values in the fast axis of <20) delivering up to 180W of pump power from each side. Even greater pump powers could then be achieved by scaling the depth and/or the length of the guide. The ultra-thin slab geometry of the waveguide is also excellent for handling the thermal loading associated with such high power pumping, giving high stress-fracture limits and low depolarisation loss, while the guide dominates the main thermal-lensing effect. No degradation in beam quality is expected in the guided axis at higher pump powers due to the careful design of the double-clad geometry [3]. In the non-guided axis the M^2 value remained stable over the power regime investigated here for output coupling <30%, but may degrade at higher powers if gain at the edges of the slab is not efficiently extracted. The use of zigzag lasing paths may help to overcome this problem, as well as improving the overall efficiency of the device. Unstable resonators are also a potential solution for high-efficiency extraction with good beam quality [6]. Efficient extraction of all the available gain is also important in minimising the potential effects of amplified spontaneous emission and parasitic lasing in these high-gain slab waveguides. These latter effects suggest that the planar waveguides will be best suited to continuous-wave or high-repetition-rate pulsed operation.

In summary, we have demonstrated the use of a stable extended cavity consisting of two cylindrical lenses and a plane mirror that can deliver high-brightness, multi-Watt output from a diode-bar side-pumped waveguide laser. Multi-mode output powers of >10W are obtained from the waveguide, at a 56% slope efficiency with respect to absorbed power. When the external cavity is optimised for beam quality, M^2 values of 1.1 (guided) by 2.8 (non-guided) are obtained and the slope efficiency is reduced to 33%, in line with theoretical expectation considering the spatial overlap of the uniformly pumped slab waveguide and the near-Gaussian lasing mode. The prospects for power scaling of this compact and high-brightness source appear to be good, due to the compatibility of the waveguide with diode-stack pumping and its thermal power handling capabilities. The use of zigzag lasing paths to fully extract the available gain and improve the spatial overlap, should lead to higher extraction efficiencies and offer further improvement in non-guided beam quality.

Acknowledgements

This work was supported in part by the award of an EPSRC grant GR/M98449. The authors wish to acknowledge O. Meissner and H. Meissner of Onyx Optics for fabrication of the waveguides used in these experiments.

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