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AN EFFICIENT HIGH-POWER WAVEGUIDE LASER SIDE-PUMPED BY TWO DIODE-STACKS

J. Wang, J. I. Mackenzie, and D.P.Shepherd
Optoelectronics Research Centre, University of Southampton, Highfield, Southampton SO17 1BJ, U.K.
dps@orc.soton.ac.uk

An in-plane diode-stack side-pumped planar waveguide laser is demonstrated. 58W of output power is obtained for 106W of absorbed pump power, from a direct-bonded Nd:YAG/sapphire double-clad guiding structure.

Keywords: waveguide lasers, diode-pumping

1. Introduction

Thin slabs are of interest for high-average-power laser systems due to their excellent power handling capabilities [1,2]. It is well known that the maximum thermal loading per unit length at which surface stress fracture occurs for a uniformly pumped slab scales with aspect ratio (width over thickness) [3]. In order to push this advantage to its extreme, one is inevitably led to the ultra-thin-slab, planar waveguide geometry. This geometry also has the advantage of overcoming the main thermal lensing effect in the slab and having a good geometrical compatibility with the diode pump source, simplifying the optics required for pump coupling.

In-plane side-pumped waveguide lasers have been demonstrated, generating powers >10W in Nd, Yb, and Tm doped YAG using proximity-coupled diode-bars [1]. To date, diode-stack pumping has only been demonstrated with relatively thick (200μm) Nd:YAG waveguides using a face-pumping technique with a reflective pump chamber to enhance the pump absorption [4]. However, the greater freedom of choice over the doping level and thickness of the guide allowed by the in-plane pumping scheme, leads to a better power scaling capability for quasi-three-level systems [2], including the important case of Yb (the dopant of choice for many high-power lasers). Here we demonstrate, we believe for the first time, diode-stack in-plane pumping of a 30μm-thick double-clad Nd:YAG waveguide laser.

2. Experimental Arrangement

The waveguide was pumped from both sides by two diode-stacks of wavelength, λ_p=808nm, from Nuvonyx Inc.. Each stack consisted of three 60W diode-bars, with each bar being individually collimated by a fast-axis (y-axis) micro-lens to deliver a beam height, D, of 6mm, and a divergence, θ_y, of 3mrad. The beam quality parameter in the fast axis, M_y^2, is given by $\theta_y D/\lambda_p \sim 22$, which was confirmed by an independent experimental measurement. In the slow axis (z-axis) the beam was approximately 11mm wide, with a very high M_z^2 value. The diodes were focused with the lenses shown in figure 1. With this arrangement we found that the light from the stacks had a 53% transmission through a 30μm-wide slit and 81% transmission through a 50μm-wide slit.

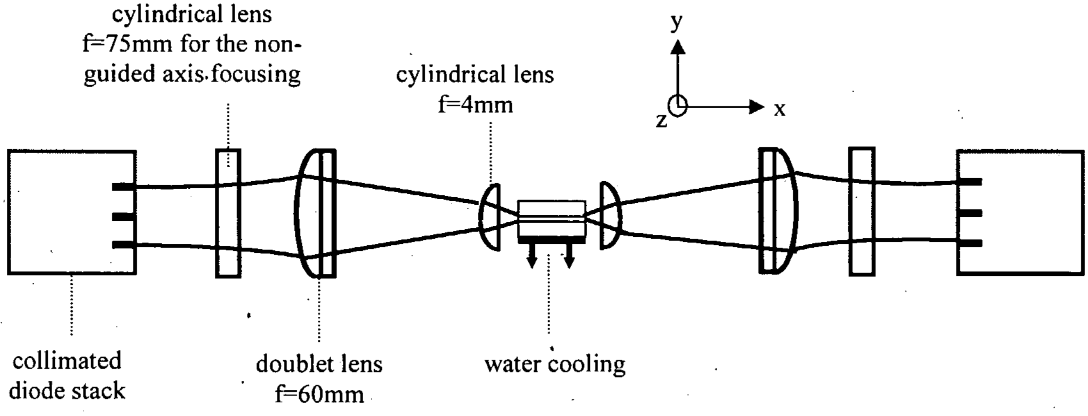

Fig. 1. Experimental arrangement for focusing the diode-stack pump light into the planar waveguide

A rough estimate of the waveguide thickness, *t*, and the numerical aperture, *NA*, required for confinement of a pump with a given M^2, can be made from $M^2\lambda_p = t.NA$. For our beam parameters and a waveguide of $NA=0.46$ (corresponding to a YAG/sapphire structure), we would expect to need a thickness of at least ~40μm. However, for this initial demonstration we used the same double-clad Nd:YAG waveguides as previously designed for use with proximity-coupled diode-bar pumping. This waveguide had a 30μm-thick pumping aperture with an *NA* of 0.46 as shown in figure 2.

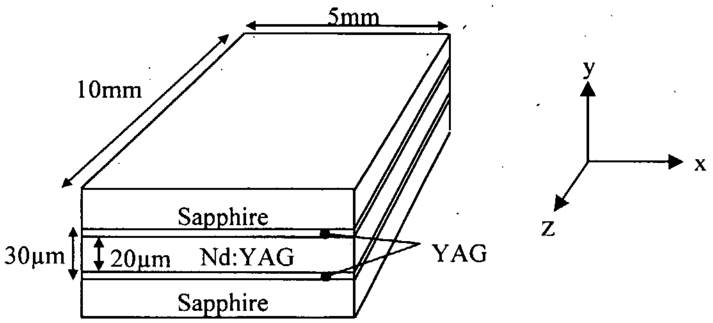

Fig. 2. Direct-bonded double-clad planar waveguide structure (fabricated by Onyx Optic Inc.)

Restricting the active dopant to the central 20μm of the 30μm-wide multi-mode waveguide has been shown experimentally [1], and theoretically [5], to robustly select fundamental mode laser operation, even under extreme signal saturation conditions. This form of cladding pumping was preferred to having an isolated single-mode waveguide within a multi-mode pumping guide (as is normally the case in double-clad fiber lasers) as the absorption length is not increased by such a large amount. The absorption length for our diode stacks in bulk 1at.% Nd:YAG was ~3mm and was expected to increase by the ratio of the waveguide thickness to the doped thickness, such that the 5mm width of the waveguide was approximately one absorption length. Thus double-sided pumping led to a relatively uniform inversion profile, with just a small dip expected in the central region of the waveguide. Given the absorption efficiency and the measured transmission through a 30μm aperture, we estimated that for these initial trials 33.5% of the incident diode pump light was absorbed. Immediate future work will use 50μm-thick guides, which should greatly improve the waveguide launch efficiency.

3. Waveguide laser performance

The laser experiments were conducted using the pumping set-up shown in figure 1 and a monolithic lasing cavity consisting of a high reflectivity (at 1.064μm) coating at one end of the guide and an 80% reflectivity coating at the other. The launch into the anti-reflection-coated side faces of the waveguide was separately optimised for each stack by adjusting the focussing optics to give the best single-sided pumping laser performance. Approximately 30W of output was obtained in this way. With the focussing of both stacks fully optimised, double-sided pumping was then undertaken with the results shown in figure 3. It can be seen that up to 58W of output power was obtained at a slope efficiency of 62% with respect to absorbed power. It should be noted that the temperature of the diodes, and hence the Nd absorption efficiency, was optimised at relatively low output power from the stack. Thus the slope efficiency may have been even higher than this value as the diode wavelength may not have been fully optimised at the highest output powers.

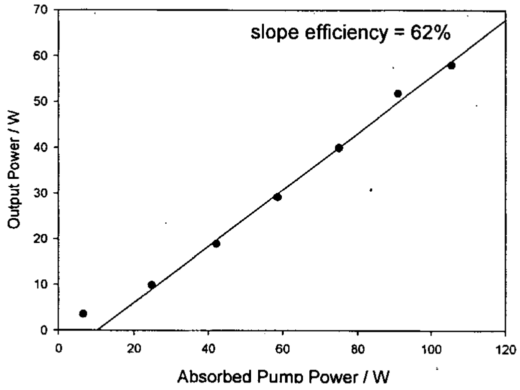

Fig. 3. Waveguide laser output power versus absorbed pump power

The expected slope efficiency with respect to absorbed pump power, η, can be calculated from,

$$\eta = \frac{-\ln R}{-\ln R + L}\frac{\lambda_p}{\lambda_s}\eta_{ol},$$

where R is the reflectivity of the output coupler, L is the round trip loss exponent, λ_s is the laser wavelength, and η_{ol} is a factor accounting for the spatial overlap of the pumped region and the laser radiation. As the pumped region was fully within the lasing mode in the guided axis and highly multi-mode output was expected in the non-guided axis, we can assume that $\eta_{ol}\sim1$. In this case an upper limit on the round trip loss exponent of 0.05 is obtained, corresponding to a waveguide propagation loss of ~0.1dB/cm, in good agreement with losses commonly found for direct-bonded waveguides of this type at 1μm [1]. We were unable to confirm the beam quality of the output, other than to note that it was single lobed, due to the occurrence of a damage process, as discussed below. However, it is expected that the fast-axis output will be robustly diffraction-limited, as found in previous experiments around the

10W level [1], and have a high M^2 value in the unguided axis. Further work will confirm this beam quality and investigate stable [6], and unstable [4], resonator designs for obtaining near-diffraction-limited performance in both axes.

As can be seen from figure 1, the waveguide was only actively cooled from one face. In this case we calculate a maximum temperature rise over the heat-sink of ~150°C due to quantum defect heating. At the maximum power shown in figure 3 we found that the upper sapphire cladding layer cleanly detached from the rest of the waveguide. Thus we were limited not by surface stress fracture but rather by the difference in thermal expansion coefficients of the YAG and sapphire layers causing the structure to separate at an estimated thermal load of 50W per square cm of cooling area. The consequent limitation on pump power could be increased by cooling from both sides and by using Yb instead of Nd to access its lower quantum defect. Thus we would expect a 10mm-long and 5mm-wide Yb:YAG waveguide to withstand absorbed pump powers ~600W, i.e. a factor of ~2 more than we can actually deliver with our present pumping arrangement (360W). Power scaling from this point could be achieved by increasing the waveguide length or moving to a MOPA arrangement. Alternative high-*NA* structures, with more closely matched thermal expansion coefficients, could also be explored.

4. Summary

In summary, we have demonstrated a diode-stack in-plane side-pumped 30μm-thick Nd:YAG double-clad waveguide laser. With single-sided cooling, 58W output power was obtained at a slope efficiency of 62%, in good agreement with theoretical expectation, until the waveguide separated at an estimated maximum temperature rise over the heat sink of ~150°C. From these results we can predict that a similar 50μm-thick Yb:YAG waveguide will easily withstand the maximum available pump power from our present pumping arrangement and that launch efficiencies >80% should be achieved. Thus output power well in excess of 100W would be available from a 1cm-long and 5mm-wide waveguide. Future work will confirm the diffraction-limited nature of the output in the guided axis and address mode control in the non-guided axis.

5. References

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