A compact high power planar waveguide laser end-pumped by a diode-bar is reported. The waveguide was fabricated by liquid-phase epitaxy and had an 80µm thick, 1.5at% Nd:Y$_3$Al$_5$O$_{12}$ core on a Y$_3$Al$_5$O$_{12}$ substrate. A maximum output power of 6.2W was obtained at 1.064µm, when the device was pumped with a 20W diode-bar operating near 807nm, giving an overall optical-to-optical conversion efficiency of 31%. The total device length was 5cm.

Rare-earth-doped crystal waveguides have the potential to yield efficient, compact diode pumped lasers and amplifiers. Confinement of the pump and the signal within the waveguide leads to a higher intensity-length product than in a similar bulk medium. This higher product gives rise to higher gains per unit pump power for the waveguide, resulting in large small-signal gains for amplifiers[1] and, if additional propagation losses owing to waveguide fabrication are small, low laser thresholds. These features could be especially useful for certain low-gain or quasi-three-level laser transitions, which can be difficult to diode-pump as bulk lasers.

In addition to the high-gain performance common to all waveguides, planar waveguides are attractive as multiwatt output power devices for several reasons. Their shape is well matched to the asymmetric output of high-power diode-bars, so the required coupling optics can be simple and compact. The thin slab structure is good for heat removal and has a higher thermal stress fracture limit than that of a rod[2]. The one-dimensional heat flow in the slab provides benign birefringence behaviour[3] and the guidance can help to counteract thermal lensing effects. With these advantages in mind we have conducted initial investigations of the performance of a 20W diode-end-pumped, Nd:Y$_3$Al$_5$O$_{12}$ (Nd:YAG) on YAG planar waveguide grown by liquid-phase epitaxy(LPE) [4].

The experimental arrangement is shown in figure 1. The diode-bar, manufactured by Opto Power Corporation, was mounted upon a water-cooled heat sink and we adjusted the coolant temperature to tune the output wavelength of the diode. At a coolant temperature of -4.0°C the diode had an output wavelength centred in the Nd absorption band, at 807.5nm, with a FWHM of 3.1nm. The output of the diode-bar was collimated in the fast divergence axis by an acylindrical fibre lens. The output beam had a collimated spot size of 162µm.

The measured divergence half-angle of the beam, $\theta_{1/2}$, were 2.3 and 2000-3000 in the fast and slow axes, respectively. To couple this pump beam into the waveguide we used an arrangement of four bulk cylindrical lenses, as shown in figure 1. The collimated output from the diode was initially expanded in the fast axis by a cylindrical x2 telescope before being focused with a cylindrical lens of 6.35-mm focal length (D in figure 1). A single 19-mm focal length cylindrical lens was used in

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**Abstract.**

A compact high power planar waveguide laser end-pumped by a diode-bar is reported. The waveguide was fabricated by liquid-phase epitaxy and had an 80µm thick, 1.5at% Nd:Y$_3$Al$_5$O$_{12}$ core on a Y$_3$Al$_5$O$_{12}$ substrate. A maximum output power of 6.2W was obtained at 1.064µm, when the device was pumped with a 20W diode-bar operating near 807nm, giving an overall optical-to-optical conversion efficiency of 31%. The total device length was 5cm.
the slowly diverging axis. This combination resulted in a line focus at the waveguide face, with measured spot sizes of 15µm and 1.3mm in the guided and non-guided directions respectively. Because of the highly divergent output from the diode-bar all measurements of spot size in this Letter, unless otherwise stated, have been defined as the aperture radius at which 86.5% of the total power is transmitted. This is a good approximation to the second moment of the intensity distribution for multimode beams[5].

The 5mm long LPE waveguide had an 80µm thick 1.5at% Nd-doped YAG core on an undoped 500µm thick YAG substrate. A further 90µm layer of undoped YAG was grown on top of the core as a protective cladding, and also to help reduce scattering losses. The Nd doping gives an index increase of 4.8x10^-4 to provide guiding behaviour. The LPE technique was shown to produce good quality waveguides, with typical losses of less than 0.1dB/cm[6].

We formed the laser cavity by directly coating mirrors onto the plane-parallel end faces of the waveguide, leading to an overall device length, from diode facet to waveguide laser output coupler, of just 5cm. The input face was nominally highly reflecting at the laser wavelength and the output face of the waveguide had a 5% transmission. The waveguide was mounted upon a water-cooled heatsink, which was operated with a coolant temperature of 15°C. A maximum output power of 6.2W at 1.064µm was obtained, for an incident pump power of 16.5W after the cylindrical lens array. At these powers no optical damage was seen on the waveguide face with CW pumping from the diode-bar.

The dependence of 1.064µm output power on diode current is shown in figure 2. The 38% conversion efficiency from incident to output power (corresponding to 31% overall optical-to-optical conversion efficiency) confirms efficient coupling of the diode-bar output into the waveguide. The maximum laser output was optimised at the maximum diode operating current. Because of space restrictions within the system, we then varied input pump power by changing the diode operating current. However this method also resulted in a change in the operating wavelength of the diode from 801nm at threshold, to 807.5nm at the peak pump power. Thus we did not plot output power versus incident pump power, as an artificially high slope efficiency would have been obtained.

Output beam M² values, measured with a Coherent Modemaster, were found to be as low as 3 and 140, in the guided and non-guided directions respectively. These values were seen to deteriorate to ~ 5 and 160 if the waveguide was mounted upon an uncooled heatsink, or if there was poor thermal contact was made between the waveguide and the heatsink, respectively. The waveguide heatsink coolant temperature was then decreased further, to 2°C, at which point condensation began to form on the waveguide, despite a constant flow of dry N₂ over the device. This cooling produced a slight improvement in beam quality in the guided direction, but no significant change in the values in the non-guided direction. The temperature change within a waveguide under pumped conditions was modeled with a one-dimensional heat-flow model. This modeling predicted temperatures near 100°C at the centre of the waveguide core, with 20W diode-bar pumping and a heatsink temperature of 15°C. This temperature falls to ~ 80°C at a heatsink temperature of 2°C.

The far-field laser mode profiles at a power of 6W and with M² values of 4 and 160 are shown in figure 3. The profiles, which we measured by scanning a thin slit across the beam, show multimode lasing, giving a rectangular output beam shape. The radius, r, of the laser spot in the far field was measured with the variance method [5].
The laser waist spot size, $W_0$, was then calculated from $W_0 = \lambda M^2 / \pi \theta_{1/2}$, where $\lambda$ is the laser wavelength, and $M^2$ represents the factor by which the divergence angle exceeds the diffraction limited value. $\theta_{1/2}$ is the ratio of the radius, $r$, to its distance $z = 27.5\text{cm}$, from the waveguide end face. This ratio results in calculated laser mode radii of $48\mu\text{m}$ and $2.3\text{mm}$ in the guided and non-guided directions respectively, indicating that the laser mode fills the $80\mu\text{m}$ by $6\text{mm}$ guide cross-section region. A calculation of the propagation of the $W_0 = 2.3\text{mm}$, $M^2 = 160$, laser beam in the non-guided direction shows that this beam is well collimated over the $5\text{mm}$ length of guide. The $W_0 = 1.3\text{mm}$, $M^2 = 2300$ pump beam expands to $W = 1.8\text{mm}$ by the end of the waveguide. Thus the pump beam remains smaller than the laser mode, allowing good energy extraction.

In these experiments we were limited in our choice of core thickness to this highly multimode guide by the availability of suitable coated waveguides. For the symmetric planar waveguide used here we calculated that the waveguide supports eleven TE and eleven TM modes at $807\text{nm}$, and eight modes of each polarisation at $1.064\mu\text{m}$. The fundamental mode beam radii ($1/e^2$ of intensity) are calculated to be $32\mu\text{m}$ at both the pump and laser wavelengths. One can assess the extent to which the guidance is playing a role in this experiment by comparing this figure for the beam radii with the minimum average spot sizes for the same length of bulk material[7]. Taking into account the $M^2$ values of the pump ($2.3$) and the laser ($\sim 3$) beams, the minimum average spot sizes are $41\mu\text{m}$ and $54\mu\text{m}$, respectively. It is clear that this size of waveguide core is close to the boundary between bulk and guided behaviour. In our future experiments we plan to use thinner waveguides.

It should be possible to improve the output beam quality by a number of different approaches while preserving, or indeed improving the compactness of the device. First, performance in the guided direction could be improved by means of focusing the pump with a single high numerical aperture graded-index rod lens instead of the cylindrical lenses shown in figure 1. Rod lenses are able to provide tighter focusing, allowing the use of thinner waveguides, which support fewer modes. Rod lenses are also compact and could lead to a simpler experimental arrangement with fewer components. Coating an unclad waveguide with a thin ($\sim 50\text{nm}$) Au layer is another method that was demonstrated to reduce the $M^2$ values in the guided direction while, in addition, producing polarised laser output [8]. A single-mode waveguide using a cladding pumping structure, and the fabrication techniques of LPE or thermal bonding [9] may also be possible.

Improvements in beam quality for the non-guided direction could be brought about by means of tighter pump focusing, for instance, with a microlens array. The high gain of these waveguide devices may also allow the use of an unstable resonator design [10]. Lateral confinement to reduce spot size and $M^2$ values could be achieved by reduction of the width of the waveguide from its present $6\text{mm}$ to a width of $2$ or $3\text{mm}$. This width more closely matches the incident non-guided pump spot size of $1.3\text{mm}$. Other rib and broadstripe structures could be fabricated by use of ion-beam etching or milling [11] techniques.

In summary, we have demonstrated a simple, compact, efficient, diode-bar-pumped planar waveguide laser. Output powers of up to $6.2\text{W}$ were achieved at $1.064\mu\text{m}$, with a $31\%$ optical-to-optical conversion efficiency. The laser had an output beam with $M^2$ values of $3$ and $140$ in the
guided and non-guided directions respectively. The whole device, from the diode facet to the end face of the waveguide was just 5cm. The brightness of the output from this multiwatt waveguide laser was ~3 times that of the diode-bar, but further significant improvements by one to two orders of magnitude, while retaining the simplicity and compactness of the overall device, are anticipated.

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References


