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Longitudinally-Diode-Pumped High-Power Waveguide Lasers

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Abstract: We describe the fabrication and use of double-clad and tapered planar waveguide structures for compact and simple, longitudinally-diode-pumped, near-diffraction-limited laser sources with output powers >1W.

Summary

The use of a planar gain region in diode-pumped solid-state lasers avoids the need to use complex beam-shapers or brightness-reducing fibre coupling to circularise the normally asymmetric diode pump beam. The slab shape also offers good thermal management and consequent prospects for power scaling. These attractive features have been studied in recent work on bulk lasers [1-3], and can be taken to their extreme in the case of a planar waveguide where, if the numerical aperture of the waveguide is high enough, the diode can simply be proximity-coupled [4]. This pumping scheme lends itself to side-pumping with diode-bars of several tens of Watts output power, and recent results have demonstrated >12W cw, and >8W passively Q-switched, waveguide laser output [5]. The output beam of the side-pumped waveguide laser is diffraction-limited in the fast-divergence axis due to the use of a double-clad waveguide [4,5]. However, for a plane-plane monolithic laser resonator, the slow axis is highly multi-mode due to the large pumped dimension of ~5mm. In this paper we describe the fabrication and demonstration of two waveguide structures that are suitable for end-pumping by 4W broad-stripe diodes to give near-diffraction-limited output in both dimensions at power levels >1W. The first method uses similar double-clad structures to those described above, and the second employs tapered waveguides. The prospects for scaling to higher powers are also discussed.

Figure 1 shows the double-clad waveguide used in our first experiments. The 5-layer double-clad structure was fabricated by Onyx Optics, Inc., using the direct-bonding method. Due to the desire to keep the pump absorption length small, the doped core to undoped inner-cladding ratio is large compared to standard optical fibre designs.

Thus the core is not optically isolated from the outer-cladding and the propagation modes of the overall multi-mode 5-layer structure must be considered. However, as the fundamental mode reaches threshold first, and has a high intensity over the central doped region, it will saturate most of the available gain preventing the higher-order modes from achieving threshold, leading to a diffraction-limited output in the guided axis.

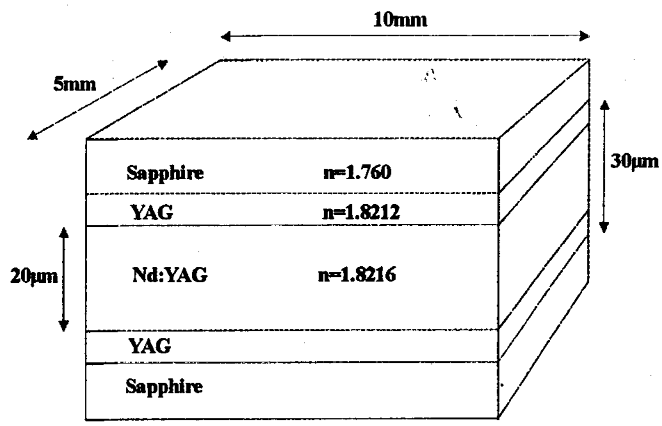

Figure 1 Double-Clad Waveguide Structure

Figure 2 shows the experimental set-up used for the diode pumping experiments. The source used was a 4W cw broad-stripe single-emitter laser diode from Boston Lasers. The diode had an emission area of 1 x 200 μm^2 and was fibre-lensed to collimate the fast axis. The beam quality, measured with a Coherent Mode Master, was found to be $M_y^2 = 3.2 \pm 0.1$ and $M_x^2 = 39 \pm 1$, in the fast and slow axes, respectively. The pumped dimension in the non-guided plane (~120μm) is much smaller than in the side-pumped case, allowing the possibility of diffraction-limited laser output. The laser resonator was formed by dielectric mirrors held onto the end-faces of the waveguide via the surface tension of a very thin layer of fluorinated liquid. The end-faces of the waveguide had been polished parallel such that the mirrors formed a monolithic plane-plane cavity. Figure 3 shows the laser output power as a function of the incident diode pump power. It can be seen that a maximum 1.064μm output power of 1.33W was obtained for 3.8W of incident pump power,

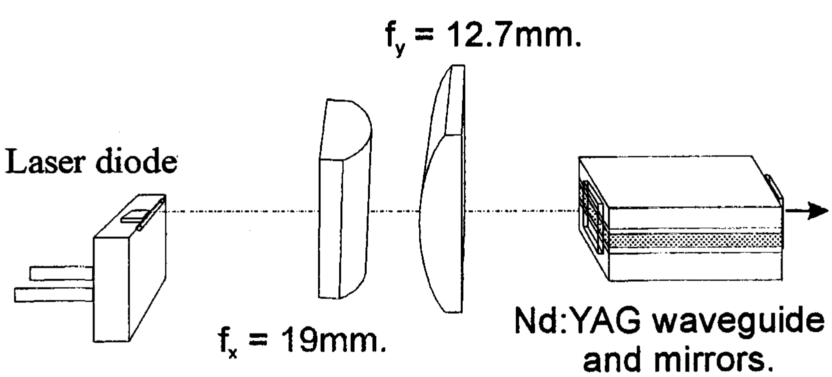

Figure 2 Experimental Arrangment for Diode-Pumping

corresponding to an optical to optical conversion efficiency of 34%. A Coherent Mode Master was used to measure the laser beam quality, which was found to be $M_y^2 = 1.0 \pm 0.1$ and $M_x^2 = 1.8 \pm 0.1$ for an output power of 1.25W.

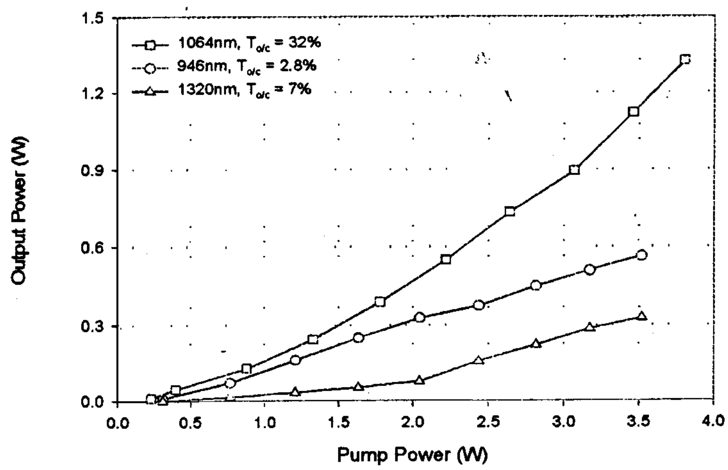

Figure 3 Output Power against Input Power

The maximum pump M^2 in the guided dimension that can be contained by a double-clad planar waveguide is given by

$$M^2 \approx D \sin^{-1}(NA)/\lambda$$

where D is the depth of the core and inner-cladding and NA is the numerical aperture of the outer-cladding to inner-cladding. Thus an M^2 of ~17 could be confined by the current 5-layer design. This may allow a higher-power pump source to be used, which has an inferior beam quality compared to the diode used here. Typical fibre-coupled diode-bars have M^2 values of ~60, which would require a guide with D~100μm for the current NA. If a design based on a higher-NA guide were used then lower values of D become possible. For instance a GGG/sapphire composite would have an NA of 0.86 and a required D value of just ~50μm.

Another route to restricting the broad gain region pumped by high-power diode lasers to a single-mode output is to use a tapered waveguide. For the taper to give an adiabatic expansion of the fundamental mode over lengths of a few centimetres, the broad end of the taper is limited to a few hundred microns in width [6]. Such dimensions are compatible with broad-stripe-diode end-pumping or, for higher powers, with diode-bar side-pumping in materials with strong absorption such as Nd:YVO_4. These structures would have the advantage, compared to the double-clad waveguides discussed above, of a strictly single-mode, and nearly symmetric, spatial output. For our initial work in this area we have demonstrated the first such planar dielectric tapered waveguide laser using ion-exchanged Nd:BK7 glass as shown in figure 4(a). With Ti:sapphire pumping and using a 20% output coupler, we obtained the results shown in figure 4(b) for a taper and a standard channel waveguide on the same substrate. These results show no

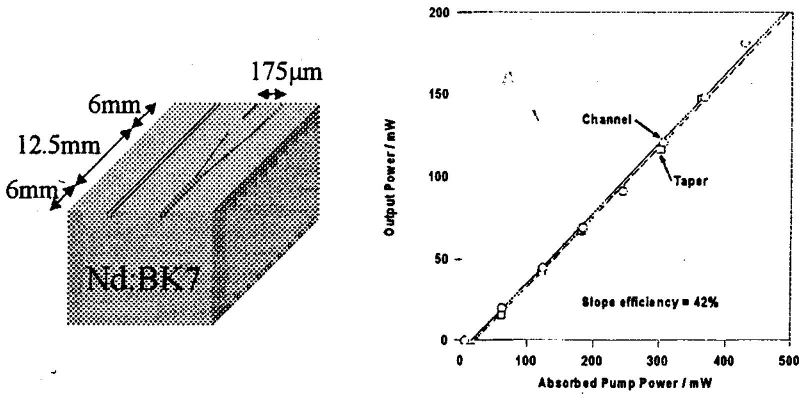

Figure 4 (a) Ion-Exchnged Channel and Taper Waveguides
(b) Output Power against Pump Power

significant additional loss for the taper and indicate an adiabatic expansion, confirmed by M^2 measurements of 1.5 x 1.5 and 1.1 x 1.0 for the output from the broad and narrow end of the tapered laser, respectively. It should be noted that the non-diffraction-limited nature of the fibre-lensed broad-stripe diode would require that the waveguide should be tapered in both axes or combined with a double-clad structure. Methods for fabricating such a guide, as well as methods of waveguide fabrication in YVO_4 for higher-power operation, are currently under investigation.

In summary, we have demonstrated efficient and compact, near-diffraction-limited, diode-pumped waveguide lasers with powers >1W and the prospects for scaling to the ~10W level appear very good.

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