# High-Numerical-Aperture, Contact-Bonded, Planar Waveguides for Diode-Bar-Pumped Lasers

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## Abstract

**We report on the design and fabrication of Nd:YAG planar waveguides suitable for in-plane, diode-bar pumping. Contact-bonded Nd:YAG on Sapphire waveguides are shown to have the high numerical aperture (0.46), low propagation loss (<0.2dB/cm), and good thermal properties necessary to make efficient diode-bar-pumped lasers and amplifiers. Coupling efficiencies of 73% and 60% have been demonstrated between a 20W diode-bar and an 8µm and a 4µm thick planar waveguide respectively, leading to 3.7W of waveguide-laser output.**

## 1. Introduction

The growing importance of diode-pumped solid-state lasers for a range of applications where cw powers of 10-100W are required, has led to many designs for the efficient coupling of the highly asymmetric and non-diffraction-limited output of high power diode-bars to various laser media. In bulk materials, beam-conditioning has been achieved via fibre-coupling [1], lens-ducts [2] and other beam-shaping optics [3]. For fibre lasers, double-clad geometries [4] and novel v-groove designs [5] have also been employed. The realisation that a slab geometry is ideal for coping with the thermal management of high power laser systems has inspired recent work on high-power planar-waveguide lasers. Two approaches have so far been reported - face-pumping of relatively thick waveguides (or thin bulk slabs) combined with a reflective pumping chamber [6] to help pump absorption, and in-plane pumping with simple cylindrical-lens beam focussing [7]. The simplicity of the latter design stems from the geometrical match between the diode-bar and the planar waveguide. However, a large waveguide core and bulk cylindrical lenses were used in that first experimental demonstration. Here we report on the design and fabrication of low-loss planar waveguides suitable for diode-bar, in-plane, pumping with much smaller core sizes (<10µm) and more compact coupling optics. Highly-efficient coupling is realised leading to multi-Watt waveguide laser outputs.

## 2. Waveguide design

In order to design an appropriate waveguide structure it is necessary first to consider the properties of the output beam of a typical laser diode bar. The emission area is normally around 1cm by 1µm with corresponding $M^2$ values of ~2000-3000 by ~1, where $M^2$ represents the factor by which the beam divergence exceeds the diffraction-limit. Two methods of in-plane coupling are immediately apparent - direct proximity-coupling, and imaging, via cylindrical lenses, of the diode-output facet onto the waveguide core. Here we will primarily be concerned with the latter, although the simplicity afforded by proximity coupling deserves future consideration. The high divergence corresponding to the 1µm emission dimension requires the use of a high numerical aperture ($NA$) cylindrical lens to give a collimated output beam suitable for refocussing into the waveguide. Typically this is achieved by attaching a fibre lens directly in front of the diode. The resulting collimated beam is typically a few hundred microns in diameter with $M^2$ values of ~2.

Let us assume that the waveguide is a step-index structure of thickness $D$. In order to launch the multi-mode ($M^2 > 1$) pump beam efficiently we must use a multi-mode waveguide with $NA$ greater than or equal to the pump beam divergence half angle:

$$NA \geq \frac{\lambda M^2}{D} \tag{1}$$

This relationship between guide depth and minimum $NA$ is illustrated graphically in fig.1 for a pump beam with $M^2$=2. Solid circles on this curve mark values of $D$ that might be used for a number of core and cladding material combinations. The guided wave gain per unit launched pump power will vary approximately inversely with $D$; thus the higher-$NA$ structures to the left of the curve derive greater advantage from the waveguide geometry. For $D$<5µm the $NA$ must be greater than ~0.3, a condition which can be met using core and cladding layers made from different materials. Structures of this type have been fabricated using contact-bonding [8] (sometimes also known as thermal-bonding). It is an ideal fabrication technique for such waveguides as it relies on the bonding of bulk materials via Van der Waals forces and so is largely independent of the material properties. Once the core material has been bonded it is then precision-polished to the desired waveguide dimensions and further cladding layers can be added as desired. The main constraint is that the materials have similar thermal-expansion coefficients as a thermal annealing step is generally applied to increase the bond strength and, in any case, thermal gradients will arise as a result of laser pumping. Other waveguide fabrication techniques which have been applied to solid-state-laser materials suitable for high-power operation, such as liquid-phase epitaxy [9] and pulsed-laser deposition [10], require that any lattice mis-match between the substrate/cladding layers and the core be very small, thus severely limiting the choice of materials. It should be noted however that

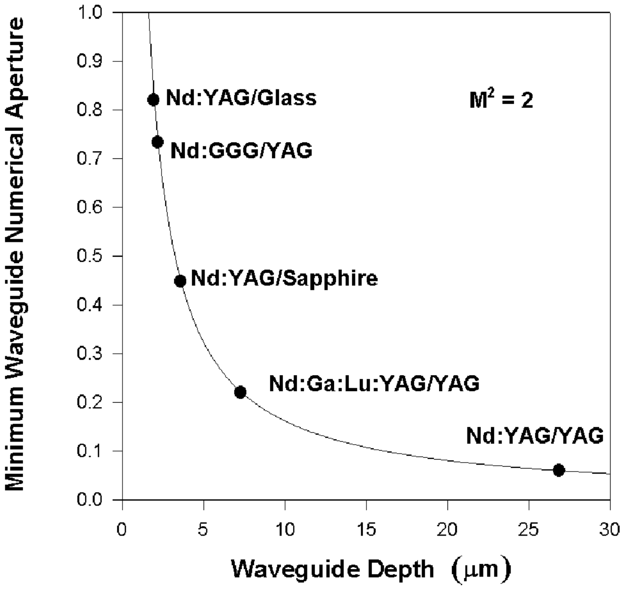

**Figure 1 A graph of the minimum waveguide numerical aperture required to confine an $M^2$=2, 807nm, pump beam in a waveguide of depth $D$.**

some material combinations do exist, such as Nd:GGG on YAG [10], that provide a large *NA* with a small lattice mis-match. Putting additional non-laser-active dopants into the core in order to increase the refractive index is another possibility [9] but this may have the effect of broadening the optical transitions of the dopant ion, giving an undesirable reduction in peak cross-section values.

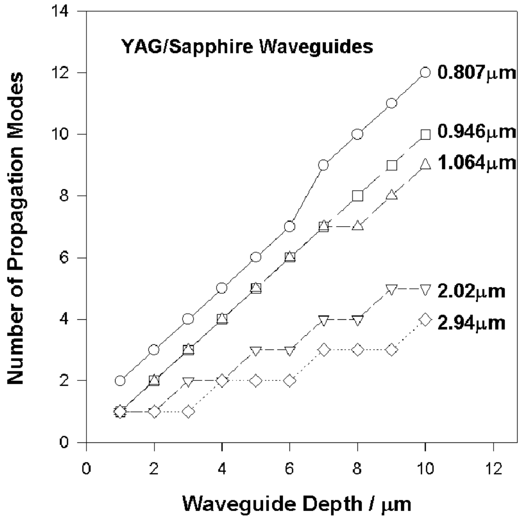

**Figure 2 Number of propagation modes against core depth for symmetric YAG/Sapphire waveguides at various wavelengths of interest.**

A Nd:YAG core with sapphire substrate and cladding layers provides a practical choice, as waveguide dimensions as small as ~4μm can be used, it has high thermal conductivity, good bonding behaviour, and high physical strength. Most applications for high-power lasers require a high-quality output beam and so operation on as few transverse modes as possible, and ideally just one, is desirable. Figure 2 shows the calculated number of TE propagation modes at some significant laser wavelengths for YAG/Sapphire waveguides of various core depths. It should be noted that the lines joining the points are only to aid the eye as the number of modes must in fact be an integer. From eqn.1 it can be seen that for ~800nm pumping of a YAG/Sapphire structure (suitable for Nd, Er and Tm dopants) the *NA* of 0.46 imposes the condition that the core-depth must be greater than 3-4μm. As we are launching a multi-mode pump beam it is not possible to use waveguides that are single mode at the pump wavelength. However, the waveguide property of having less propagation modes at higher wavelengths can be helpful in keeping the number of modes at the output wavelength small, especially in cases such as the 2μm Tm:YAG and 3μm Er:YAG emissions. If truly single-moded outputs are required (in the guided-direction) cladding-pumped structures could also be fabricated by the contact-bonding method.

## 3. Diode bar to waveguide coupling

The coupling optics used to launch pump light into the waveguide must also be of sufficiently high *NA*. Figure 3 shows a schematic diagram of the simple and compact optical system used in our experiments. A graded-refractive-index rod lens from Doric Lenses Inc., designed to be corrected for spherical aberration up to an *NA* of ~0.5, is used as the re-focussing element, c, in the guided plane and a single 19mm focal length cylindrical lens, b, is used in the other plane. This led to a diode-waveguide distance of <3cm. For our initial investigations of coupling efficiency we used Nd:YAG on sapphire, asymmetric slab waveguides, with core sizes of 4μm and 8μm, fabricated by Onyx Optics Inc. via contact-bonding. Both these 2cm-long waveguides were made to lase with Ti:Sapphire

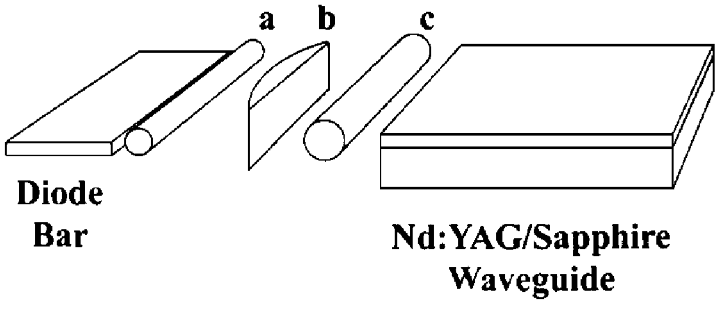

**Figure 3 Schematic diagram of the diode to waveguide coupling experiments. The lenses are: a collimating fibre lens (a), a bulk cylindrical focussing lens (b), a re-focussing rod lens (c).**

end-pumping and, by measuring the threshold versus the output coupling [11], the propagation losses at 1.064µm were determined to be <0.2dB/cm for the 8µm guide and <0.5dB/cm for the 4µm guide. For diode-bar pumping, rod lenses of various focal lengths were used for each guide in order to optimise the launch efficiency, and the guides themselves were mounted on a water cooled heat-sink. A lower limit to the launch efficiency was determined by assuming that 100% of the launched light was absorbed (a good approximation as the absorption length for the diode pump light was measured to be 3.4mm). A simple measurement of all the power before and after the waveguide when the diode-beam is optimally coupled, and accounting for Fresnel reflections, is then all that is required to find the launch efficiency. Experimentally, it was found that, of the rod lenses available to us, a 1.027mm focal-length rod gave the best coupling efficiency for the 8µm guide and a 0.685mm focal-length rod was the optimum choice for the 4µm guide. The $M^2$ of the 20W, 807nm, diode-beam was measured to be 1.5 and the final line-focus was approximately 4mm by 2-4µm (aperture diameter at which 86.5% of the total power was transmitted). The lower limits to the optimum launch efficiency were found to be 73% for the 8µm guide and 60% for the 4µm guide. Thus it is clear that both guides can be coupled to the diode-bar output very efficiently.

## 4. Waveguide Laser Results

To provide further confirmation of the high coupling efficiency a laser resonator was constructed around the 8µm guide by butt-coupling two thin mirrors to the polished end-faces. The input mirror was highly-reflecting at 1.064µm and transmitted 92% at the 807nm pump wavelength. The output mirror was nominally 50% reflective at 1.064µm. A laser output power of 3.7W was obtained from this resonator with measured $M^2$ values of 10 (guided direction) by 85 (non-guided). Significant improvements in the beam quality could be made in future by the use of smaller waveguides supporting fewer modes as described above, through cladding-pumped structures, and by use of an unstable resonator geometry for the unguided direction. Higher output powers should also be obtainable by using a shorter length of waveguide (the guides used in the experiments were several absorption-lengths long, thus contributing significant excess loss), by optimising the output coupling, and, of course, via higher pump powers. The latter could be in the form of higher-power diode bars or by using multiple bars in a side-pumped geometry (multi-Watt outputs have already been observed from side-pumped waveguide lasers [12]).

## 5. Summary

In summary we have shown that in-plane, diode-bar pumped planar waveguides offer the possibility of very simple and compact, multi-Watt, laser devices. Contact-bonding has been shown to be an effective technique for fabricating waveguides with the high NA required for efficient diode-waveguide coupling, with the low propagation losses required for good laser operation and the ability to handle high average power. A composite of YAG/Sapphire, in particular, has been shown to be an attractive candidate for high-power waveguide lasers. Efficient diode to waveguide coupling has been demonstrated in such structures for core sizes as small as 4µm, and multi-Watt waveguide laser outputs have been obtained.

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