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# A 15W Diode-Side-Pumped Tm:YAG Waveguide Laser at 2μm


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## Abstract

We report the high-power side-pumped operation of a double-clad Tm:YAG waveguide laser at 2.02μm, using two proximity-coupled 20W diode pump lasers. A slope efficiency of 43% was observed with respect to incident diode power, giving a maximum output power of 15W. The double-clad geometry ensures diffraction-limited output in the guided plane.

*Introduction:* Laser sources with wavelengths around 2μm are of interest for medical, military, and eye-safe remote sensing applications. Thulium is an attractive candidate for laser operation at this wavelength as it has a strong absorption at 785nm suitable for pumping by AlGaAs laser diodes and, for doping levels of a few atomic percent, an efficient cross-relaxation process leading to two ions in the upper laser level for every pump photon. Thus high slope efficiencies can be achieved despite the large quantum defect [1]. However, the $^3F_4$-$^3H_6$ laser transition has a low emission cross-section and is quasi-three-level in nature. Thus a relatively intense pumping is required, often leading to the use of end-pumped geometries [2,3]. Here, we demonstrate a double-clad Tm:YAG waveguide laser that allows intense diode-pumping in a very compact, power scalable, side-pumped geometry. 15W of output power is obtained when side-pumping with two proximity-coupled 20W diode bars, with a slope efficiency of >40% with respect to incident power. The output is diffraction-limited in the guided dimension due to the structure of the waveguide but, at present, is highly multi-mode in the non-guided plane.

*Experiments and results:* The direct-bonded double-clad planar waveguide structure detailed here and shown in figure 1, is similar to those described previously for $Nd^{3+}$- and $Yb^{3+}$-doped YAG [4,5]. A 20μm-thick 10at.%-$Tm^{3+}$-doped YAG core, was direct bonded to two 5μm-thick undoped YAG inner cladding layers. Sapphire substrates were also direct bonded to form the outer cladding layers. The width and length dimensions were 0.5cm and 1cm respectively. Laser cavity mirrors were coated directly onto the flat end-faces of the waveguide with an output coupler transmission of 10% at 2.02μm. The side-faces of the waveguide were tilted by ~3° (with respect to the vertical axis) to prevent parasitic lasing in the plane of the waveguide, and were anti-reflection coated at the pump wavelength. The large index difference between sapphire and YAG produces a high numerical aperture (~0.47) multi-mode guide capable of confining the highly divergent output from the diode-bars. A small refractive index difference of $\sim 1 \times 10^{-3}$ was also expected between the doped core and undoped inner cladding layers, although this has a negligible effect on the guiding properties.

Two cw diodes from Coherent Inc. were proximity coupled to the waveguide on custom alignment fixtures from Maxios Laser Corporation. These diodes had a centre wavelength of 785nm and produced up to 44W of combined power. They were water-cooled, along with the waveguide mount, through a common base plate. Laser threshold was found at 8W incident pump power. The resulting maximum output power was 15W, corresponding to an optical to optical efficiency of 34%, and with a measured slope efficiency of 43% with respect to incident power. Single-pass absorption of the diode pump radiation was measured to be 71%, implying a slope efficiency with respect to absorbed power of 61%. Figure 2 shows the results for both double-sided and single-sided pumping with the main difference being a slightly higher threshold for the single-sided pumping case. For the absorption value measured here, the gain distribution in the unguided plane is expected to be relatively uniform (within 20%) for double-sided pumping, while the single-sided pumping has much stronger gain near the pumped side. The intensity profiles of the output in the guided and unguided axes were measured by scanning a 250μm square InAs PIN photodiode across the beam, whilst monitoring the voltage output from a matched amplifier. Single traces of the intensity profile at the beam centre for the respective axes are shown in figure 3. A comparison is made between the guided and unguided axes for single- and double-sided pumping. The guided modes are a very good fit to a Gaussian distribution and do not vary with power or the pumping scheme. In the non-guided plane the double-sided pumping leads to a symmetric near-Gaussian output, whereas the single-sided pumping gives an asymmetric mode with the peak intensity shifted towards the pumped side.

The beam dimensions were determined via a second moments analysis. By tracing the beam as it propagated from the output and fitting the Gaussian propagation curve to the results, it was determined that the guided axis had an $M^2=1.1\pm0.1$, however for the unguided axis the $M^2$ was >300. The diffraction-limited nature of the output in the guided axis is due to the fact that the gain is restricted to the central portion of the guide, selecting fundamental mode operation of the highly multi-mode guide [6]. No attempt has been made to control the mode in the non-guided axis, which has a high Fresnel number due to the 5mm-wide gain region. Future work will aim at implementing unstable resonator designs to control the spatial mode in this axis [5]. As previously observed in other double-clad waveguides [4,5], the laser output was partially polarised, with a ratio of 9:1 TE:TM polarisation. Although not confirmed experimentally, it is believed that this partial polarisation may be a consequence of stress birefringence from the direct bonding fabrication process.

*Conclusions:* We have demonstrated efficient, high-power, diode-pumped operation of a 2μm Tm:YAG waveguide laser. The 5-layer structure leads to diffraction-limited output in the guided plane and double-sided pumping is shown to be useful for both power scaling and the production of a more uniform gain distribution, leading to a smoother output spatial profile in the non-guided plane. Further power scaling could be achieved using a longer length guide allowing more diode pumps and through the use of higher power diode bars. Such power scaling will be facilitated by the excellent thermal handling capabilities of the slab geometry [6] and a predominantly one-dimensional thermal lensing that is dominated by the waveguide itself.

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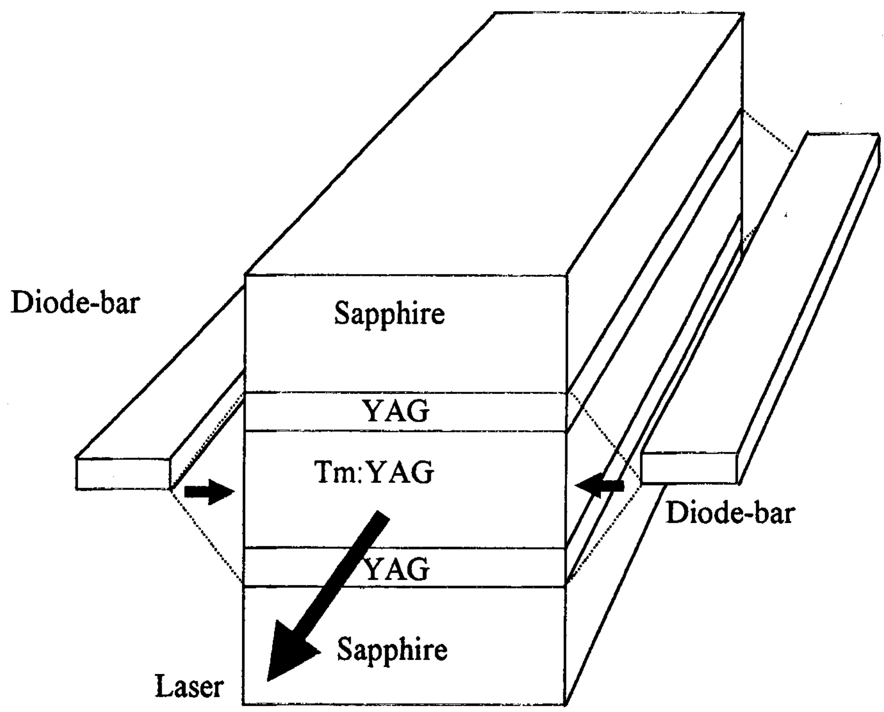
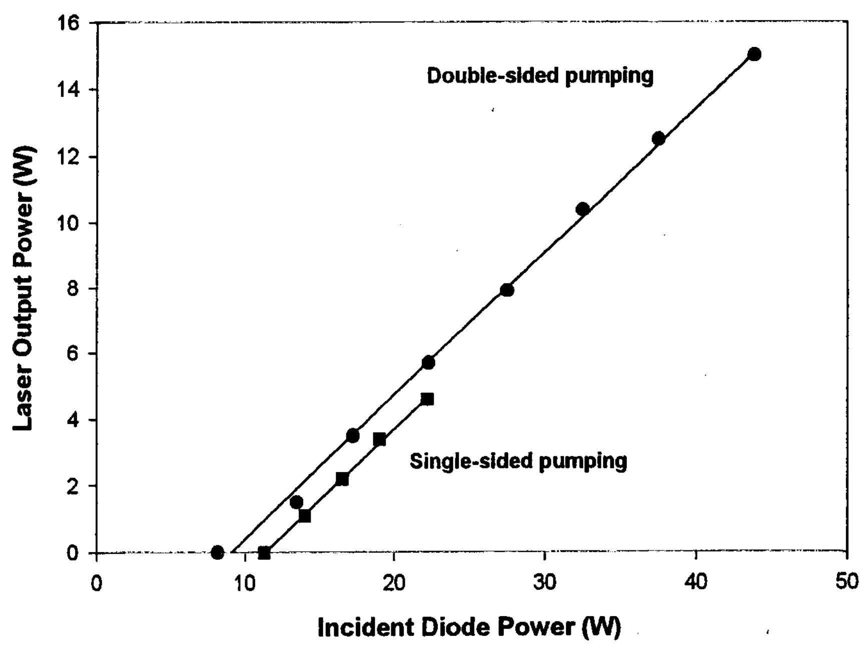
**Figure Captions**

Figure 1 Schematic diagram of the experimental set-up and the 5-layer waveguide structure.

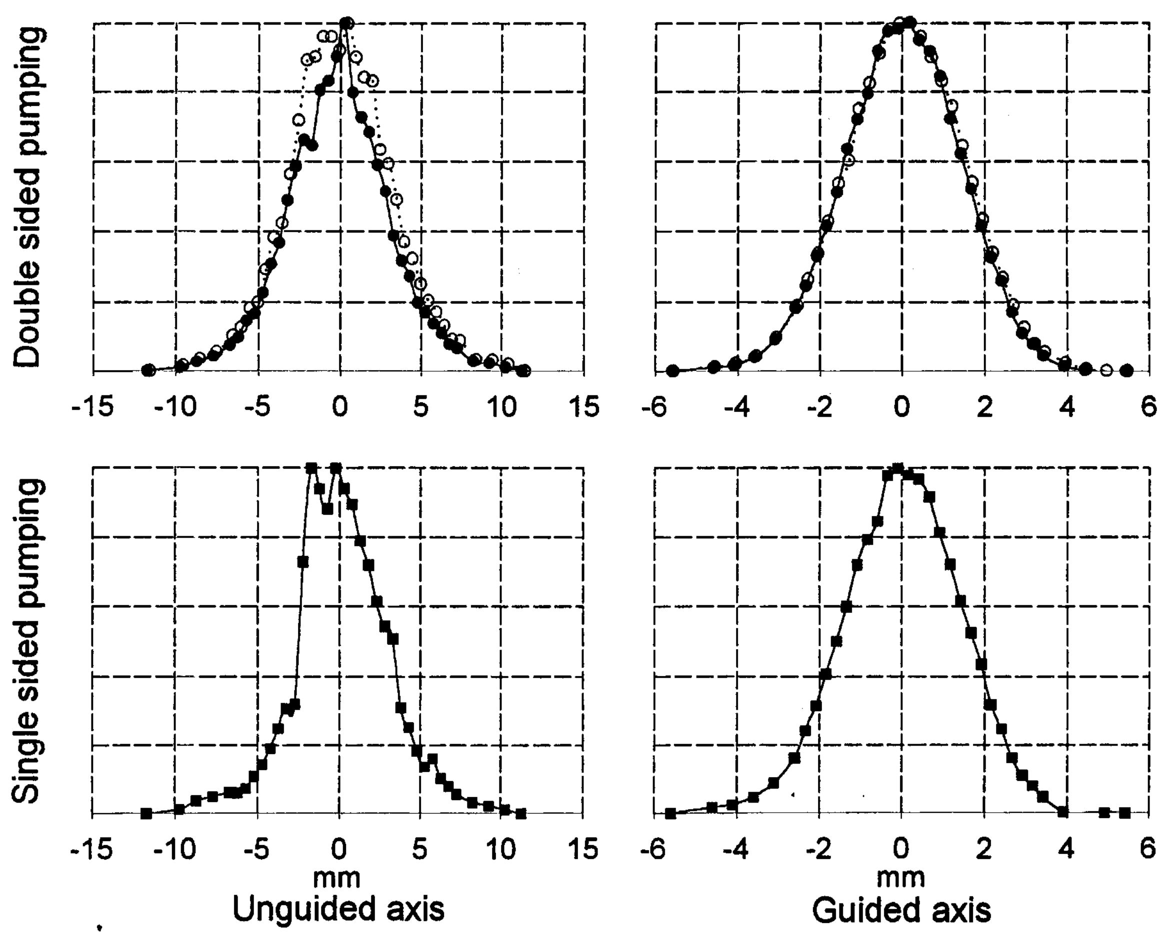
Figure 2 Output power characteristics.

Figure 3 Beam profile scans 40mm from the cavity mirror. A comparison between double- and single-sided pumping is made for both the guided and unguided axes. The spatial profiles for the double-sided pumping for 15W ( o ) and 4W (—•—) output power are shown. The latter power being the maximum achievable with single-sided pumping.


Diode-bar
Sapphire
YAG
Tm:YAG
Diode-bar
YAG
Sapphire
Laser



Double-sided pumping
Single-sided pumping
Laser Output Power (W)
Incident Diode Power (W)
0
2
4
6
8
10
12
14
16
0
10
20
30
40
50



Double sided pumping
Single sided pumping
-15 -10 -5 0 5 10 15
-6 -4 -2 0 2 4 6
mm
Unguided axis
Guided axis