High-Power and Ultra-Efficient Operation of a 946nm Nd:YAG Planar Waveguide Laser

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Abstract: A high-power and ultra-efficient 946nm Nd:YAG double-clad planar waveguide laser is reported. The laser produced 35W of output for 68W of incident pump power with a corresponding slope efficiency of 57%.

OCIS codes: (140.3530) Lasers, neodymium; (140.3480) Lasers, diode-pumped

Introduction

Power-scaling quasi-three-level laser transitions is of interest for their potential to achieve high efficiency with reduced thermal loading and thus ultimately, improved laser performance from a smaller system footprint. In addition, the $^4F_{3/2}\rightarrow{}^4I_{9/2}$ transition of Neodymium is attractive as it provides an output wavelength below 1micron, which can be frequency doubled into the blue-green part of the visible spectrum for applications in areas ranging from, underwater sensing and communications, display technologies and information storage, to biological or medical diagnostics. Nd:YAG has been the active host medium of choice for investigation of this transition [1-3], due to its excellent thermo-mechanical and thermo-optical properties. In a bulk laser configuration the relatively low gain for this transition, along with the modest reabsorption losses, demand high-brightness pump sources. Notwithstanding, even for such sources, the thermal loading density associated with the pumping cycle limits the achievable 946nm performance due to the significant increase in the crystal's temperature, and hence, the strong and highly aberrated thermal lens that arises.

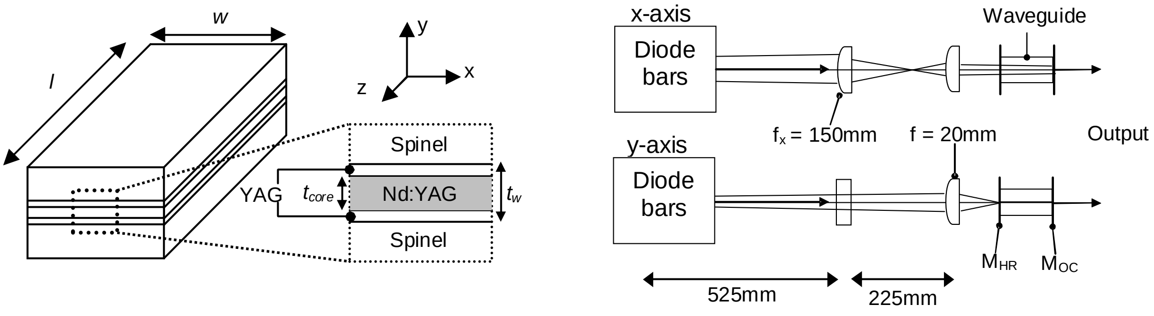
In this paper we report a double-clad Nd:YAG planar waveguide, with its inherently exceptional thermal management, which produces 35W of output power at a wavelength of 946nm, when end-pumped with two 808nm diode bars at an incident power of 68W. This corresponds to a 52% optical to optical conversion efficiency and 57% slope efficiency with respect to the incident pump power.

Experimental set-up

The double-clad planar waveguide used in this experiment was fabricated by Onyx Optics Inc. (Dublin, California), using their proprietary Adhesive-Free Bonding (AFB®) technique, a schematic of the composite is illustrated in Fig. 1(a). The in-plane dimensions of the waveguide were 5mm x 20mm (w x l), the multi-mode 5-layer composite structure comprised Spinel as the outer-cladding (~2.5mm thick), two un-doped YAG inner-cladding layers (18microns thick), and a 0.6at.% Nd:YAG core (t_{core} = 35microns thick). As such the cladding waveguide numerical aperture (NA) is >0.5 and supports 90 modes, while the core has a calculated NA = 0.03 and is expected to support 3 modes for a wavelength of 946nm. The effective doping ratio is ~50%, implying that the 20mm length is approximately two absorption lengths for the 808nm diode pump source. The large NA and effective overall waveguide aperture of t_w = 70microns could, in principle, efficiently capture nearly all of the incident pump power of a stack of 6 diode-bars (or twice this number with polarisation multiplexing); however, such a source was not available at the time of this experiment. Due to the in-plane aspect ratio of the crystal, parasitic lasing paths exist that are trapped within the waveguide through total internal reflection at each of the side (end) faces. As such, the side faces of the waveguide were finished with a fine grind to frustrate any reflections.

A water-cooled copper mount clamped the waveguide's top and bottom surfaces, two thermal interface films provided a low thermal-impedance between these surfaces and the copper. The side faces were not in contact with the copper block to ensure vertical heat flow from the core layer. Butting thin mirrors up to the uncoated end-faces of the waveguide, a quasi-monolithic resonator was configured. The mirrors were coated on one surface only and were held in place with metal springs, the pump in-coupling mirror (M_{HR}) had an 80% transmittance (T) at the pump wavelength and ~1%T at 946nm, while the output-coupling mirror (M_{OC}) had a ~5%T for the pump and 13%T at the lasing wavelength. Both mirrors were highly transmitting around 1.06microns corresponding to the much stronger four-level transition.

Two optically-stacked, low-fill-factor diode bars, collimated in both axes with fast-axis and slow-axis collimation micro-optics, delivered a maximum power of ~85W at a wavelength of around 808nm. A simple pump coupling scheme was employed, consisting of a cylindrical lens, f_x = 150mm, and an a large aperture aspheric lens, f = 20mm, the lenses positioned as shown in Fig. 1(b). This combination produced a pump beam, at the front facet of the waveguide, with second moment beam diameters of ~2.1mm x 40µm, for the in-plane (x-axis) and guided-plane (y-axis) respectively. Effectively a top hat intensity distribution was obtained in the x-axis, with little diffraction spreading along the crystal length and the image-plane of the diode bars occurring after the waveguide, thus providing a uniform pumping distribution in this direction. In addition, in the guided y-axis the pump beam is rapidly homogenised by the waveguide, thus there were no hot spots within the active region that might damage the crystal or introduce strong thermal distortions.



(a) (b)

Fig. 1 (a) Waveguide schematic and (b) experimental set-up.

Results and Discussion

As shown in Fig. 2, the laser threshold for the 946nm transition was around 2W of incident pump power, where the incident power is taken to be the power incident upon the waveguide facet, i.e. taking into account the transmission of the pump-in-coupling mirror. The output power increased in a linear fashion (when the pump power was several times that needed to reach threshold, as is expected of lasers with reabsorption losses [1-2]) with a slope efficiency of η_s = 57%. Such a high slope efficiency illustrates the low propagation-loss properties of these waveguides [4], with the obvious benefit that the converted light is primarily extracted as useful output rather than lost in the waveguide. At most of the data points in Fig. 2, the diode temperature was adjusted to ensure that the pump wavelength was constant, and similarly the absorption efficiency, apart from the highest two points where the temperature of the diodes could only be held at a temperature a few degrees higher than the optimum and where the absorption efficiency dropped by several percent. A maximum output power of 35W was obtained for 68W of pump power. To our knowledge this is a factor of two improvement in respect to the highest reported output power for this laser transition [3], limited only by the appropriate pump power.

Multimode operation of this laser was confirmed for both guided and unguided axes, through beam quality measurements. In the guided axis M_y^2 = 2.8, while in the unguided axis M_x^2 = 56. It is expected that an external cavity can be configured to produce a fundamental mode of the appropriate dimensions that would match well the ~1mm radius gain-width in the plane. Moreover, with careful mode matching the fundamental guided mode could be isolated with the same cavity. Similarly, for a quasi-monolithic laser configuration optimised for 1064nm operation, the respective beam quality was M_y^2 = 2.1 and M_x^2 = 33, with a maximum output of 46W for 78W of incident pump power, for which the slope efficiency was η_s = 60%. As expected for the longer wavelength, where the core waveguide supports only two modes, there is a better guided beam quality, however, the improved unguided axis beam quality was primarily dependent upon the mirror contact and position, thus it is considered that with further optimisation the 946nm brightness could be similarly improved.

The lasing wavelength was confirmed with an optical spectrum analyser and no evidence of output at 1064nm was observed. Although, in the case of poor mirror contact where the 946nm lasing was not fully extracting all of the available gain, 1064nm output was observed and appeared to be amplified spontaneous emission (ASE) rather than laser action.

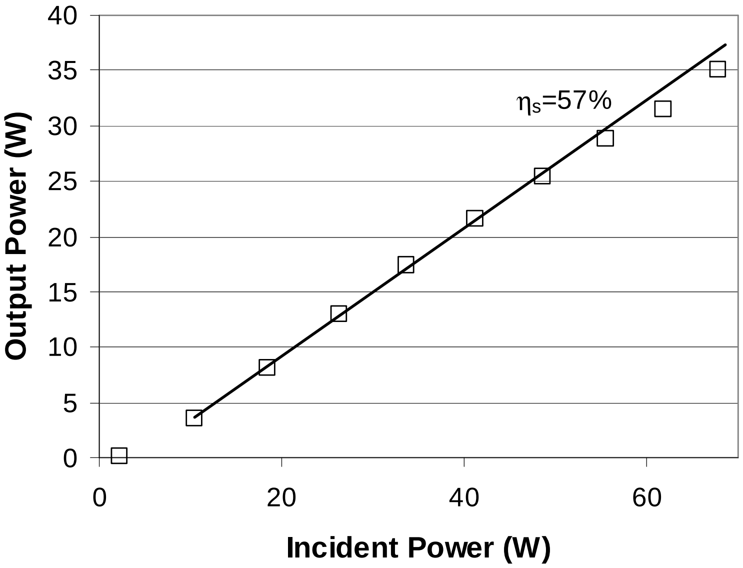


Fig. 2: 946nm Nd:YAG laser performance with a 13%T output coupler.

Conclusions

Herein we have demonstrated the advantage of the double-clad planar waveguide structure for ultra-efficient and high-power operation of a diode-pumped Nd:YAG laser, especially for the relatively weak quasi-three-level $^4F_{3/2}\rightarrow{}^4I_{9/2}$ transition. These results and the more than factor of two improvement in output power with respect to equivalent bulk lasers illustrates the keys benefits to be derived from a guiding structure and its excellent thermal management. Ultra-efficient operation at a wavelength of 946nm was obtained with an output of 35W for 68W of incident pump power and a slope efficiency of 57%. Similarly impressive performance was obtained for the standard 1.064μm $^4F_{3/2}\rightarrow{}^4I_{13/2}$ transition as well, with 46W of output for 78W of incident pump power. Reasonable guided mode beam quality was observed with several options to improve this characteristic, along with excellent expectations for further power scaling.

Acknowledgements

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