Longitudinally diode-pumped Nd:YAG double-clad planar waveguide laser

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We report the demonstration of a near-diffraction-limited, compact, diode-end-pumped double-clad planar waveguide Nd:YAG laser. Efficient laser operation was achieved for the three dominant Nd^{3+} transitions, at 1.064, 0.946, and 1.32 μm, with TE polarized output powers of 1.33, 0.57, and 0.33 W for the available output couplers. The output beam from the monolithic plane–plane laser cavity had measured M^2 values of 1.0 and 1.8 perpendicular and parallel, respectively, to the plane of the waveguide. © 2001 Optical Society of America

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Planar waveguides are well suited to acting as host structures for diode-pumped solid-state lasers because of a combination of features related to their slablike geometry. The use of a planar end-pumped gain region avoids the need to use beam shapers or brightness-reducing fiber coupling to shape 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 research on bulk lasers[1–3] and can be taken to their extreme in the case of a planar waveguide, for which, 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 >12 W of continuous-wave and >8 W of passively Q-switched waveguide laser output. The output beam of the side-pumped waveguide laser is diffraction limited on the fast divergence axis owing to the use of a double-clad waveguide[4]; however, for a plane–plane monolithic laser resonator the slow axis is highly multimode. In this Letter we describe end pumping of similar double-clad waveguides by a 4-W broad-stripe diode, leading to near-diffraction-limited output in both dimensions at output powers greater than 1 W. The prospects for scaling to higher powers are also discussed.

The Nd:YAG waveguide used in this experiment is the same as that described in Ref. 4 and is shown schematically in Fig. 1. The five-layer double-clad structure was fabricated by Onyx Optics, Inc., by the direct-bonding method. The waveguide structure consists of a weak inner guide formed by a 20-μm-thick neodymium-doped YAG core (1 at. % Nd) sandwiched between two 5-μm-thick undoped YAG layers, which compose the inner cladding. Two 4-mm-thick sapphire layers form the outer cladding and provide excellent thermal conduction away from the doped core. The neodymium doping in the core provides a refractive-index increase, $\Delta n \approx 0.0004$, with respect to the undoped cladding, leading to a numerical aperture (NA) of $\approx$0.04. A greater refractive-index difference is present between the sapphire and the YAG, $\Delta n \approx 0.06$, giving a NA of $\approx$0.46. Because of the desire of keep the pump absorption length small, the doped core–to–undoped inner cladding ratio is relatively large compared with those of standard optical fiber designs. Thus the core is not optically isolated from the outer cladding, so the propagation modes of the overall multimode five-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 and leading to a diffraction-limited output in the guided axis.

The propagation loss of the waveguide was investigated by end pumping with a Ti:sapphire laser and measurement of the 1.064-μm laser threshold for a variety of output couplers.[4] The inset in Fig. 2 shows the results for laser cavities consisting of two highly reflecting mirrors, one highly reflecting and one end-face Fresnel reflection (~8%), and two Fresnel reflections. The loss value is obtained from the intercept on the

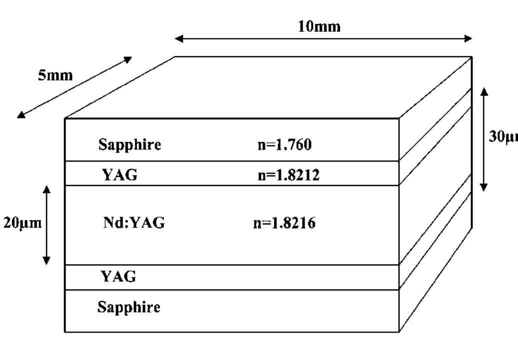

Fig. 1. Schematic of the double-clad waveguide geometry.

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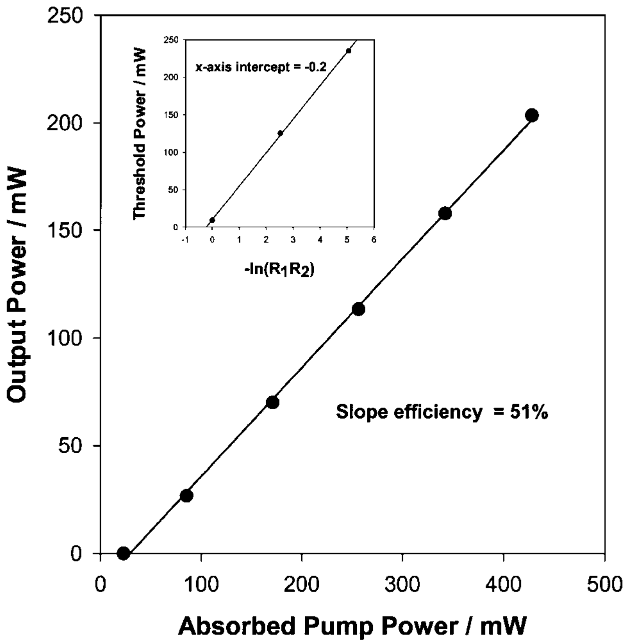

Fig. 2. Plot of output power versus absorbed pump power for the Ti:sapphire-pumped waveguide laser. Inset, plot of threshold incident pump power versus output coupling.

x axis, for which the percentage error could be rather large. Nevertheless the intercept clearly indicates a low loss, equivalent to a few tenths of a decibel per centimeter. To confirm this value we also measured the output slope efficiency and found it to be as high as 51% for an $R = 82\%$ output coupler (Fig. 2), where R is reflectance. The upper limit for the slope efficiency is given by

$$\eta \leq \frac{\lambda_p}{\lambda_l}\left(\frac{-\ln R}{L - \ln R}\right), \tag{1}$$

where λ_p and λ_l are the pump and the laser wavelengths, respectively, and L represents the other round-trip cavity losses. Thus we can put an upper limit on L of 0.1, which corresponds to 0.2 dB/cm and agrees well with previously found values for direct-bonded waveguides.[4]

Figure 3 shows the experimental setup used for the diode-pumping experiments. The source used was 4-W cw broad-stripe single-emitter laser diode from Boston Lasers. The diode had an emission area of 1 μm × 200 μm and was fiber lensed to collimate the fast axis. The diode spectrum had a width of ~1.5 nm and, when it was used to pump the double-clad structure, led to a measured absorption coefficient of ~2 cm^{-1}. The beam quality, measured with a Coherent Mode Master beam analyzer, was found to be ${M_y}^2 = 3.2 \pm 0.1$ and ${M_x}^2 = 39 \pm 1$ in the fast and the slow axes, respectively. The laser diode output was coupled into the double-clad waveguide via two cylindrical lenses of local lengths $f_x = 19$ mm and $f_y = 12.7$ mm for the slow and the fast axes, respectively, chosen through optimization of the waveguide laser power. The corresponding calculated pumping spot size (second-moment radius) for the unguided plane was 57 μm, whereas the guided pumped dimension was set by the 20-μm-deep doped core. The positions of the lenses and the waveguide were also optimized for best output power performance.

The laser resonator was formed by dielectric mirrors held onto the end faces of the waveguide by means of the surface tension of a 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, 10 mm in length. For each laser transition studied, the input mirror was highly reflecting at the lasing wavelength and had high transmission for the pump wavelength. Only a limited number of output coupler mirrors were available for the two weaker transitions, ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ ($\lambda_1 = 946$ nm) and ${}^4F_{3/2} \rightarrow {}^4I_{13/2}$ ($\lambda_l = 1.32$ μm), where selection was based on achieving a lower laser threshold with respect to the dominant transition, ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ ($\lambda_l = 1.064$ μm). In contrast, for the $\lambda_l = 1.064$-μm transition a wide range of output coupler mirrors was available, permitting a true optimization for maximum waveguide laser output power. The output couplers used for the transitions were $\lambda_l = 1.064$ μm, $T_{oc} = 32\%$; $\lambda_l = 946$ nm, $T_{oc} = 3\%$; $\lambda_l = 1.32$ μm, $T_{oc} = 7\%$, where T_{oc} are the output coupler transmissions.

Figure 4 illustrates the laser output power results as a function of the incident diode pump power. It can be seen that a maximum 1.064-μm output power of 1.33 W was obtained for 3.8 W of incident pump power, corresponding to an optical-to-optical conversion efficiency of 34%. The slope efficiency cannot be calculated directly from Fig. 4, as the wavelength of the diode was seen to vary significantly with current

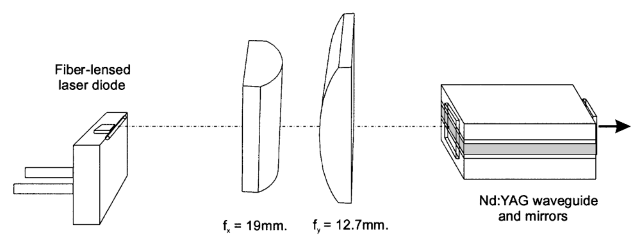

Fig. 3. Schematic diagram of the diode end-pumping arrangement.

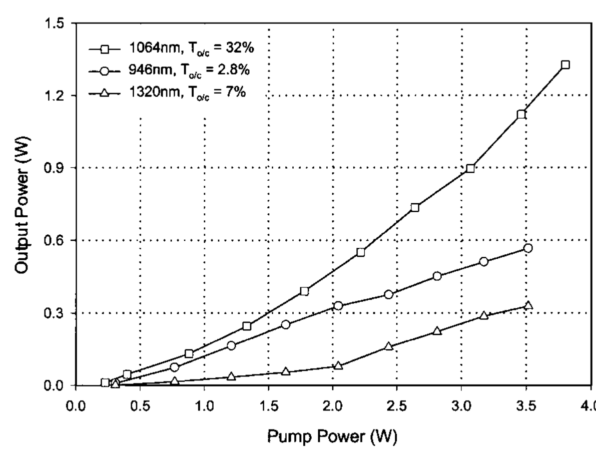

Fig. 4. Plot of the diode-pumped waveguide laser output power versus incident pump power for three transitions in Nd:YAG.

and hence with output power. However, the best absorption, of $\sim 2 \text{ cm}^{-1}$, was obtained at the maximum output power. A Coherent Mode Master beam analyzer was again 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 1.25 W. Using a Cohu CCD camera and a Coherent BeamView analyzer, we recorded a beam profile, from which the beam's $1/e^2$ intensity radii at the output mirror were determined to be $W_y = 10 \pm 1\ \mu\text{m}$ and $W_x = 165 \pm 5\ \mu\text{m}$. Thus the laser beam is well collimated over the cavity length and is larger than the pump beam over a distance comparable with the experimentally measured absorption length assuming, that the pump waist is inside the gain medium as would be expected for optimum performance. It is possible that further optimization of the nonguided pumping spot size could have lead to a slightly lower M^2 value in this plane. Thermal lensing effects, typical for high power diode-pumped lasers, would effectively produce aberrated cylindrical lenses of different focal lengths in the two axes of the waveguide.[3,5] Assuming cooling through the large faces of the slab, the major thermal lens will be in the same plane as the guidance. Baker *et al.*[6] have shown that the pump power per unit volume required for a thermal lens that overcomes the guidance will scale inversely with the core thickness to the power of 4. For the particular materials and pumping geometry described here, that limit will not be reached until pump powers exceed ~100 W. The effect of any thermal lensing in the less tightly focused, nonguided plane has not been quantified, and future research will investigate this property, especially for higher-power operation, such that it may be incorporated into laser cavity design.[3] It should be noted that the relatively high output beam asymmetry could easily be made circular with cylindrical lenses if required. The laser output was found to be nearly linearly polarized, with a ratio of power of approximately 9:1 between TE and TM states. This unexpected polarization behavior was previously observed in both Nd- and Yb-doped double-clad direct-bonded waveguides.[4]

A lower maximum output power of 0.57 W (for 3.5-W incident power) was observed for the quasi-three-level transition, $\lambda_l = 946$ nm, as shown in Fig. 4. This lower efficiency was the result of using a higher-reflectance output coupler. The use of output coupling nearer the 30% value used for the 1.064-μm lasing is certainly possible and would significantly improve the conversion efficiency. Finally, for the $\lambda_l = 1.32$-μm transition the output power was lower again (0.33 W for 3.5-W incident power), despite use of a larger output coupling than for the 946-nm lasing. This result is, at least in part, due to the larger quantum defect.

By relating the NA of a waveguide to the divergence angle of a beam passing through an equivalent aperture, we can calculate the maximum allowed pump M^2 value that can be contained by a double-clad waveguide as

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

where D is the width of the core and the inner cladding and the NA is that of the outer cladding to the inner cladding. Thus M^2 values of ~17 could be confined by the current five-layer waveguide design. If a design based on a higher-NA guide were used, even higher M^2 beams could be confined. For instance, a gadolinium gallium garnet/sapphire composite would have a NA of 0.86 and could confine a beam with M^2 values of ~60 for a D value of just ~50 μm, close to that used here. This beam confinement may allow a higher-power pump source to be used that will have an inferior beam quality compared with the diode used here. A more straightforward scaling of the output power of this laser to a few watts should also be possible by polarization coupling of two broad-stripe diode sources for single-ended pumping. Further performance improvements could be expected if the crystal facets were directly coated with dielectric mirrors rather than the butted mirrors that were used for convenience in these experiments.

In conclusion, we have demonstrated a simple longitudinally pumped double-clad planar Nd:YAG waveguide laser with 1.33-W output power at 1.064 μm in a near-diffraction-limited beam, $M^2 = 1.0 \times 1.8$. Laser action was also demonstrated for the weaker 0.946- and 1.32-μm transitions. Output powers of 570 and 330 mW, respectively, were measured, and improved performance for these transitions can be expected with optimized mirrors. The simplicity, excellent thermal properties, efficiency, and robust design of this device make it an attractive candidate for multiwatt diffraction-limited performance for a range of laser wavelengths. Scaling to higher powers also appears to be feasible by use of a modified double-clad waveguide designed to permit the use of lower-beam-quality diode pump sources.

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