2459

An End-Pumped, Passively Q-Switched, Yb:YAG Double-Clad Waveguide Laser

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Abstract

We present a diode-pumped, double-clad Yb:YAG waveguide laser that contains an integrated section of Cr^{4+}:YAG saturable absorber for passive Q-switching. Using two 4W polarisation-coupled, broad-stripe, diode pump lasers we obtained 30μJ pulses of 1.6ns duration, at repetition rates of up to 77kHz. The slope efficiency was ~50% with respect to absorbed pump power, with a maximum output average power of 2.3W and a peak power of ~18kW. The output beam was single-lobed with M^2 values up to 1.5 by 1.3. We also demonstrate a passively Q-switched Nd:YAG waveguide laser of similar design, operating at 1.064μm and 946nm.

Double-clad planar waveguides are attractive as hosts for high-power diode-pumped lasers due to a combination of features including excellent thermal management properties, diode-compatible geometry, high optical gain, and good spatial-mode selectivity[1,2]. Efficient continuous-wave operation of various laser transitions has been demonstrated in side-[3,4] and end-pumped[5] configurations, and side-pumped passively Q-switched operation has been demonstrated in Nd:YAG at 1.064μm[6]. Yb:YAG is attracting growing interest as a competitor to Nd:YAG for high power sources due to its low quantum defect, broad absorption and emission lines, lack of upconversion losses, and comparatively high saturation fluence[7,8]. Passive Q-switching of bulk Yb:YAG to obtain compact sources of high peak power has been achieved using semiconductor saturable absorber mirrors[9] and Cr^{4+}:YAG as a saturable absorber[10,11] . Here we demonstrate the first operation of a double-clad Yb:YAG waveguide laser with an integrated Cr^{4+}:YAG section for passive Q-switching. Highly efficient operation is achieved, with near-diffraction-limited output, when pumped by two polarisation-coupled broad-stripe diode lasers. We also briefly describe passively Q-switched laser operation of a similar Nd:YAG double-clad waveguide at both 1.064μm and 946nm and show that its performance is inferior to that of Yb:YAG in this regime.

The structure of the 1cm-long waveguide, fabricated by Onyx Optics using the direct bonding technique, is shown schematically in figure 1. The high numerical aperture, multi-mode, YAG/sapphire waveguide allows easy coupling of high-power diode sources, while restricting the 10at.% Yb^{3+}-doping to the central YAG layer leads to preferential operation on the fundamental spatial-mode[2]. A Cr^{4+}:YAG section, situated centrally in the core region, acts as a saturable absorber to provide passively Q-switched operation. The saturable absorber is 540μm long and has an absorption coefficient of 4.34 per cm at 1.064μm, which we assume is similar to that at 1.03μm[8].

Two polarisation-coupled broad-stripe diodes operating around 914nm act as the pump source for these experiments (see figure 2). This wavelength is less efficiently absorbed than the more commonly used pump wavelengths of 941nm and 968nm but is still sufficient for our purposes. The diode output beams are collimated in both axes using two cylindrical lenses (C1 and C2) and combined, after polarisation rotation of one via a half-wave plate, at the polarising beam splitter (PBS). For an electrical power of 16.3W the source supplies a maximum optical power of 7.2W incident on the first cylindrical beam-conditioning lens (C3). The final spherical focussing lens (FL) provides measured second-moments beam-radii waists of 8μm in the guided (y)-axis and 100μm in the unguided (x)-axis, with measured M^2 values of 3.8 and 21, respectively. The y-axis waist is situated at the entrance to the waveguide and the x-axis waist lies just over 3mm inside the waveguide. The waveguide has coatings directly applied to its polished end-faces to give a plane-plane laser cavity with a 20% reflectivity output coupling mirror (OC) at the pump input end, and a highly reflecting mirror (HR) at the other end. The orientation of these mirrors means that the signal is directed back towards the pumping optics and requires the use of a dichroic mirror (D) to extract useful output.

From measurements of the unabsorbed transmitted pump power, and knowledge of the transmission of the optics and coatings at the pump wavelength, we were able to calculate the absorbed pump power (assuming 100% launch efficiency).

The peak wavelength of the diode emission, which has a ~5nm bandwidth, changes with increasing current from 908nm to 914nm, with a constant diode cooling temperature, and the single-pass absorption was measured to increase from 0.6 to 0.79. These figures are consistent with reported absorption cross-sections in this wavelength range and the reduced absorption due to the double-clad structure[7,12].

Figure 3 shows the average output power versus diode power (incident on lens C3) characteristic for this laser. A maximum of 2.3W output was obtained at a slope efficiency of 46%. The efficiency with respect to absorbed power (~50%) is only slightly higher than this value due to the changing absorption efficiency. The onset of pulsed laser output occurred at a pump power of 1.37W and just below this threshold ~10mW of continuous wave output was observed. Figure 3 also shows how the pulse repetition frequency increases approximately linearly to a maximum value of 77kHz. The error bars indicate the increase in timing instability at the high frequencies. This behaviour has been reported previously[6] and was attributed to the fact that, at such high frequencies, the time between pulses approaches the lifetime of the excited state of the Cr^{4+} ion. Figure 4 shows a typical pulse train from the passively Q-switched waveguide laser using a slow detector such that the variation observed is due to variation in pulse energy, which itself is attributed to the variation in the timing of the pulse switching. Measurements of the full-width half-maximum pulsewidth using a fast detector indicated stable values with a small decrease from just over 2ns to 1.6ns with increasing pump power. Both the pulse energy and the peak power show a steady increase with pump power up to values of 30μJ and 18kW respectively. This behaviour is consistent with that reported for previous passively Q-switched Yb^{3+}-doped lasers using Cr^{4+}:YAG as a saturable absorber[9,10,13]. The highest intensity generated in the waveguide is ~2×10^{13} Wm^{-2} and no damage was observed to the waveguide or coatings.

The output beam quality was assessed in the x- and y-axes using a dual slit Gentec Beamscope and measuring the beam radii around the foci of a spherical lens of 150mm focal length. The output beam was first collimated in the unguided axis using a 150mm cylindrical lens, noting that in the guided axis the beam was already well collimated by the pump focussing optic (FL). The required attenuation was achieved via a single reflection from an uncoated glass wedge and additional reflective filters. The M^2 values were found to increase from 1.0 in both axes near threshold, to 1.5 (x-axis) by 1.3 (y-axis) at high power. Thus, the double-clad waveguide structure, which is designed for strict fundamental spatial-mode selection under continuous-wave operation[2], is still effective in this Q-switched regime. The output was typically found to be >95% polarised in the y-axis.

The pulsewidth, pulse energy and repetition rate are in good agreement with the predicted results using the analysis of Patel and Beach[8] when a value of ~0.3ms is used for the upper-state lifetime. This value is ~3 times less than the normally used value and may be due to the effect of amplified spontaneous emission (ASE) in the high numerical aperture waveguide[6]. By decreasing the small signal transmission of the Cr^{4+} saturable absorber the same analysis suggests that pulse energies >100μJ and pulsewidths of <300ps, at pulse repetition rates of ~10kHz, are feasible from the same set up. However, limitations due to ASE may come into effect.

For comparison, the performance of a similar Nd^{3+}-doped double-clad waveguide was investigated. Operation at 1.064µm gave very unstable output in terms of repetition rate, pulse energy and double-pulsing. The pulsewidths were typically around 10ns, again in agreement with theory. The unstable behaviour is thought to be due to the fact that the theoretical repetition rate is >100kHz soon after onset of laser operation. The modelling suggests that even with very high values of small-signal Cr^{4+} absorption it is difficult to achieve repetition rates below 100kHz and that pulse energies are generally low. Operation at 946nm was also obtained but similar unstable operation was observed as well as considerable ASE at 1.064µm. Improved performance could be obtained using a relatively high reflectivity output coupler (97%R), but only with relatively low pump power. Thus it appears that the small mode-area of the waveguide geometry makes it unsuitable for passive Q-switching of Nd:YAG using a Cr^{4+}:YAG saturable absorber. However, larger mode volumes, such as in a diode-bar side-pumped waveguide[6], will allow such operation.

In summary we have demonstrated a diode-end-pumped Yb:YAG double clad waveguide laser with an integrated Cr^{4+}:YAG saturable absorber for passive Q-switching. A train of pulses with peak powers ~18kW (30µJ energy and 1.6ns duration) was obtained in a linearly polarised, near-diffraction-limited beam. The maximum average output power was 2.3W with a slope efficiency of ~50%. The performance of the Yb:YAG Q-switched laser agrees well with theoretical expectation and is found to be superior to that of Nd:YAG at 1.064µm and 946nm in this operating regime. This compact and highly efficient source could be useful for applications involving marking and nonlinear optical generation.

This work was supported in part by the award of an EPSRC grant GR/M98449. The authors wish to acknowledge O. Meissner and H. Meissner of Onyx Optics for fabrication of the waveguides used in these experiments, and R. J. Beach of Lawrence Livermore National Laboratory and F. Patel of Agilent Technologies for help with the modelling of the passively Q-switched lasers.

Figure Captions.

Figure 1 Schematic diagram of the double-clad waveguide used in these experiments.

Figure 2 Experimental arrangement for diode-pumping: broad-stripe diode lasers DL, cylindrical collimating lenses C1 (f_y=1mm) and C2 (f_x=4mm), half-wave plate $\lambda/2$, polarising beamsplitter PBS, beam conditioning lens C3 (f_x=75mm), focussing optic FL (f=6.5mm), and dichroic mirror D.

Figure 3 Graph of pulse repetition frequency and average output power against diode pump power incident on lens C3.

Figure 4 Trace of typical output pulse train.

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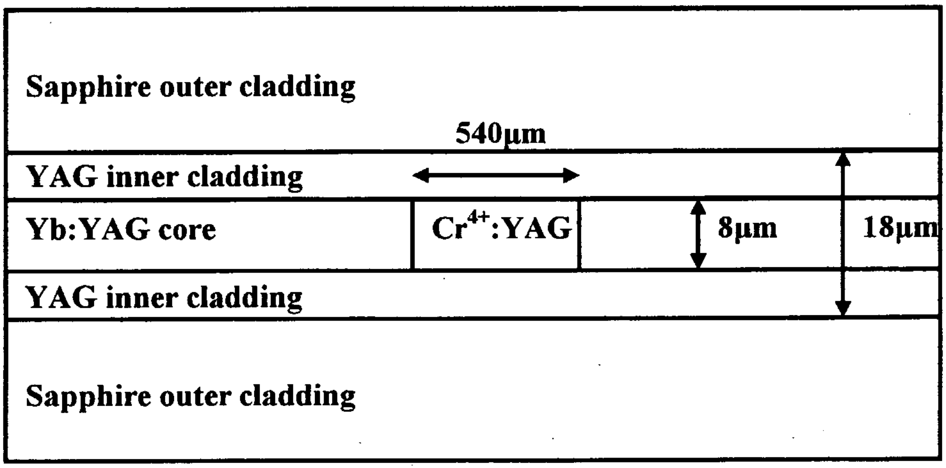
Sapphire outer cladding
540μm
YAG inner cladding
Yb:YAG core
Cr4+:YAG
8μm
18μm
YAG inner cladding
Sapphire outer cladding

Figure 2 J.I.Mackenzie et al Optics Letters

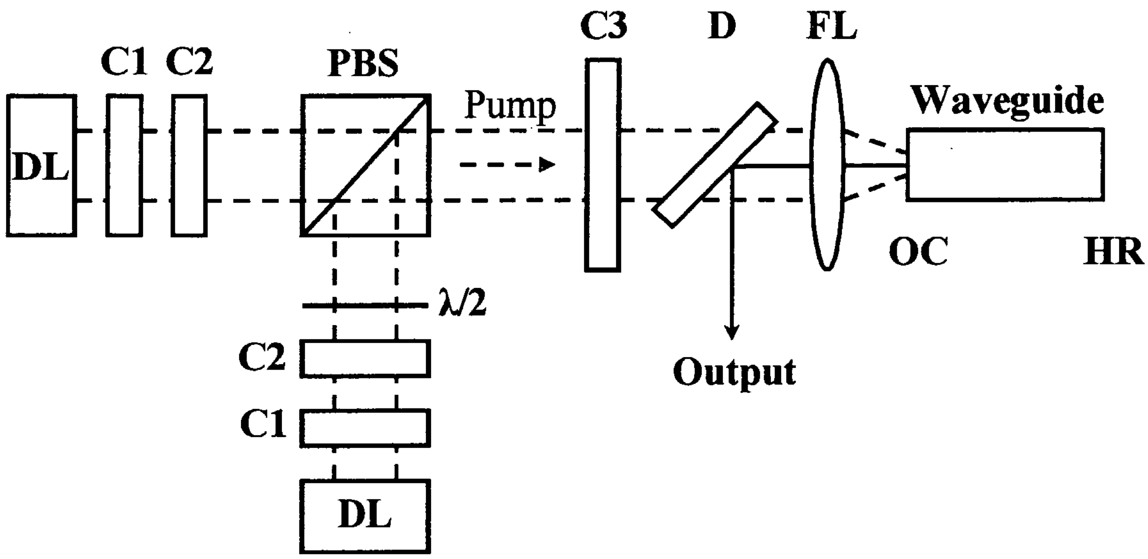

Figure 3 J.I.Mackenzie et al Optics Letters

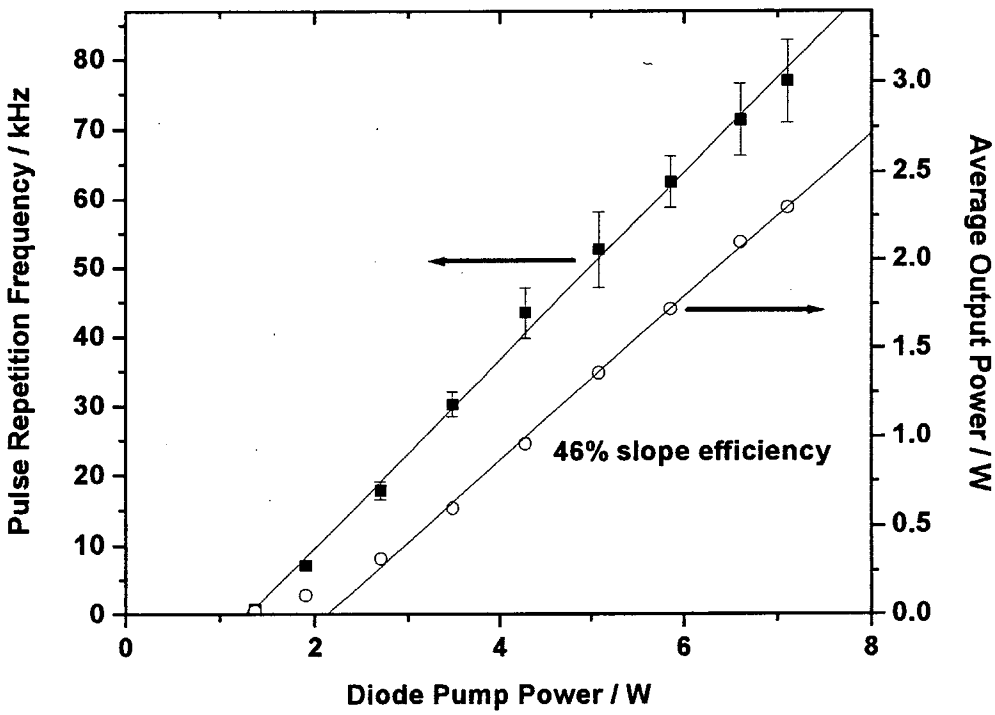

Figure 4 J.I.Mackenzie et al Optics Letters