340

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Quasi-three level 1.03 μm laser operation of a planar ion-implanted Yb:YAG waveguide

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The first laser operation of an Yb:YAG waveguide is reported. Room temperature, continuous wave operation was achieved at a threshold of 30 mW. Projected thresholds of a few milliwatts for a channel waveguide indicate that for quasi-three level lasers, a waveguide configuration, even if lossy, can be highly beneficial.

Efficient, room temperature, diode-pumped, operation of a 1.03 μm Yb:YAG bulk laser has recently been reported [1,2]. Yb:YAG has several interesting features that could give it advantages over the widely used Nd:YAG system. Figure 1 shows the energy level diagram for this laser from which it can be seen that the pump wavelengths are closer to the laser wavelength than is the case for the 1.06 μm transition in Nd:YAG, leading to a more efficient transfer of energy from the pump to laser photons and less thermal loading of the gain medium. Also, as ytterbium has only one excited 4*f* manifold, problems associated with excited-state absorption, upconversion and concentration quenching should be eliminated. The latter means that high doping levels can be achieved (>20 at.% [2]) without any reduction in fluorescence lifetime which, at 1.16 ms, is longer than found for Nd:YAG. The broad absorption bands of ytterbium are also well suited to diode pumping.

Three-level lasers, and quasi-three level lasers (of which Yb:YAG is an example) have the drawback of an increased threshold due to absorption of the laser light by population in the lower laser level, ~4% of the total population in the case of Yb:YAG. However, it is possible to overcome this drawback by confining the pump and laser light within a waveguide, so that the required intensity can be achieved at low pump powers. While such waveguides usually introduce an additional propagation loss this will be

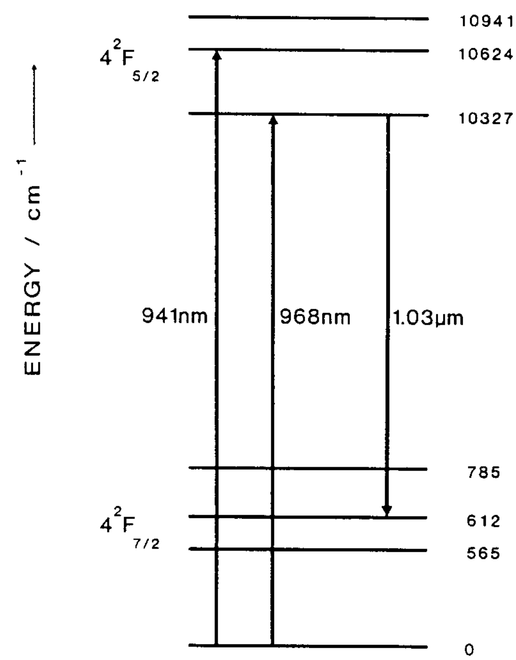

Fig. 1. Energy level diagram of the Yb:YAG system.

of less consequence than for a four-level laser since the absorption loss may be comparable to or even dominate the waveguide loss [3]. To confirm this point, of general applicability to (quasi-)three level lasers, we have chosen Yb:YAG as a suitable illustration.

Several methods exist for the fabrication of laser waveguides in YAG, including crystal fibre growth [4], epitaxial growth [3,5], and ion-implantation [6]. Here we report planar waveguides made by ion-implantation and discuss the implications that the results obtained have for channel waveguides fabricated by the same method. The Yb:YAG used in these experiments is similar to that described in ref. [1] having a 6.5 at.% doping level. The crystal was cut into a 10 mm×5 mm×2 mm block and one of the 10 mm×5 mm faces was polished to allow implantation. The waveguide was created by implanting He^+ ions through this surface with a dose of 3×10^{16} ions/cm^2 at 2.65 MeV, and 0.75×10^{16} ions/cm^2 at 2.3 MeV, 2.1 MeV, 1.9 MeV, and 1.7 MeV. This was followed by annealing for one hour at 250°C to remove any colour centres formed during the implantation. From measurements of the dark mode pattern, observed by prism coupling to the waveguide, the refractive index profiles shown in fig. 2 were deduced [7]. These are similar to those found with Nd:YAG having a larger index increase in the guiding region for the TM polarisation than for TE.

The waveguide was carefully end polished to produce a scratch free surface up to and including the top few μm of the crystal where the waveguide was situated. After end polishing the crystal was ~7 mm long and an end launched transmission of ~50% was observed at ~600 nm for both TM and TE polarisations. Taking into account the end face Fresnel reflections and an assumed launch efficiency of ~80%, as has previously been observed with similar size guides, this transmission indicates propagation losses of ~2 dB/cm. This is slightly higher than those found in optimised ion-implanted Nd:YAG waveguides [8], and may be reduced in future by optimisation of the implant/annealing conditions.

The emission spectrum of the Yb:YAG waveguide was investigated by end launching pump light at 941 nm from a $Ti:Al_2O_3$ laser and focusing the output into a monochromator. Figure 3 shows the resulting fluorescence spectra from the bulk and waveguide regions. We were unable to take the full spectrum in this region without picking up the tail of the pump radiation. Thus we were unable to scale the two complete spectra to have the same area underneath the line. This would allow an accurate measurement of the change in emission cross-section between the bulk and waveguide. However the spectra in fig. 3 have been scaled to have the same area over the region shown and it is clear that the waveguide spectrum is broadened and we can estimate that the peak emission cross-section is reduced by a factor of ~1.5. The absorption spectrum was also seen to be somewhat broadened. Measurements of the fluorescence lifetime in the waveguide region found no observable difference from the bulk value of 1.16 ms. The spectral broadening, with no change of fluorescence lifetime, is typical of the behaviour observed in many laser materials following ion-implantation. The transmitted 941 nm pump was observed with a CCD camera connected to a beam profile analyser (Big Sky Software Corporation beamview analyser). The output was single mode with a spot size ($1/e^2$ half width of intensity) of ~2.5 μm.

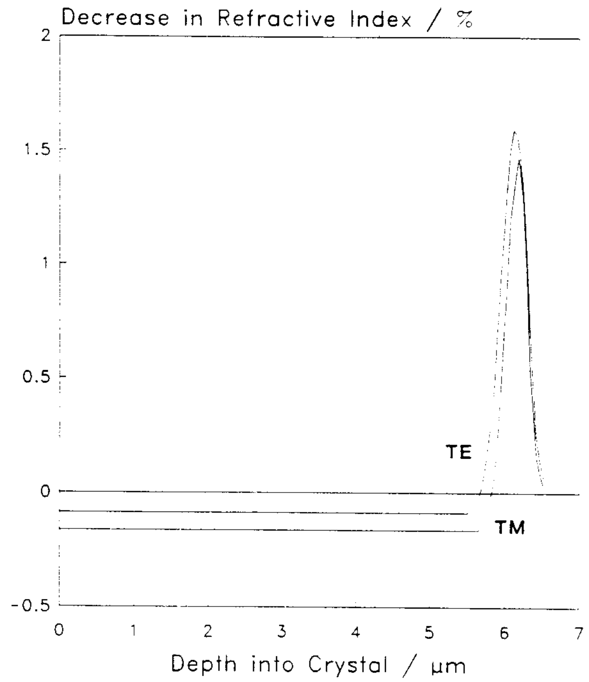

Fig. 2. Refractive index profile of the ion-implanted planar Yb:YAG waveguide.

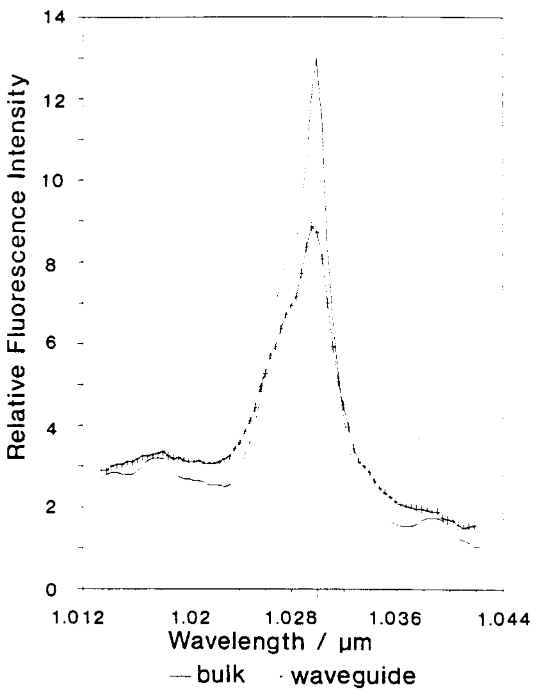

Fig. 3. Fluorescence spectra of the bulk and waveguide regions around 1.03 µm.

In order to test the laser performance of the Yb:YAG waveguide it was cut and end polished to a length of 1.65 mm (one absorption length in the bulk material) matching the experimental conditions used in ref. [1]. Care was taken to make the end faces parallel as these define the laser cavity. A $Ti:Al_2O_3$ laser was used for the pump source. The experimental set up was as shown in fig. 4. The laser cavity was formed by butting thin, light-weight, high reflectivity mirrors directly against the end faces of the crystal. These mirrors were held in place by the surface tension of a drop of fluorinated liquid [6]. The output from the waveguide was focused into a monochromator so that the 1.03 µm Yb^{3+} fluorescence and laser signal could be separated from the unabsorbed 941 nm pump light. Laser action was observed at a launched power of ~56 mW. Assuming that the absorption cross-section in the guide region is reduced similarly to the emission cross-section and taking into account the waveguide loss, the useful absorption of the pump over a single pass is only 46%. However the output mirror reflected 34% of the left over pump light raising the overall absorption of the launched light to ~53%. For future experiments either a slightly longer length or more effective feedback of the unabsorbed pump will be used. Thus the absorbed power threshold was calculated to be ~30 mW. Observation of the output mode with a CCD camera was made possible by spatially separating the left over pump light and the laser signal with the use of two dispersing prisms. The output was single mode with guided and unguided spot sizes of 2.5 µm and 29 µm, respectively. As found with ion-implanted Nd:YAG waveguide lasers the output is TM polarised due to the difference between the refractive index profiles for the TM and TE polarisations leading to a lower cut-off wavelength for the TE polarisation. The polarisation of the pump source made no observable difference to the laser threshold. A calculated threshold can be obtained from the below expression for quasi-three level lasers [9],

$$P = \frac{\pi h\nu (W_{sx}^2 + W_{px}^2)^{1/2} (W_{sy}^2 + W_{py}^2)^{1/2}}{4\sigma\tau} \times (L + T + 2N_1^0 \sigma l)\,, \qquad (1)$$

where σ is the reduced emission cross-section (1.2×10^{-24} m^2), N_1^0 is the equilibrium population density of the lower laser level (3.95×10^{25} m^{-3}), W are the averaged laser (s) and pump (p) spot sizes [10] in the guided (y) and unguided (x) planes (W_{sy}, $W_{py}=2.5$ µm, $W_{sx}=29$ µm, $W_{px}=62$ µm as

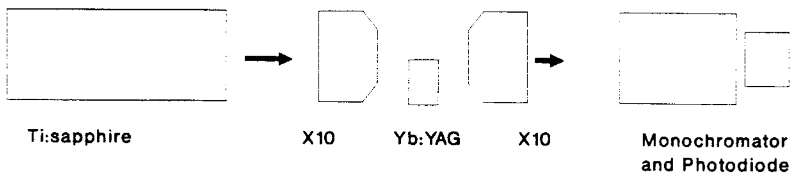

Fig. 4. Schematic side-view of the experimental set-up used to test waveguide laser performance.

the focused pump beam spreads considerably in the unguided plane), ν is the pump frequency, τ is the fluorescence lifetime, l is the crystal length, L is the fixed cavity loss (0.152), and T is the output coupling. Putting the experimental values into eq. (1) leads to a calculated absorbed power threshold of 9 mW. We believe that the main source of the discrepancy between the calculated and observed threshold is likely to be imperfect feedback from the butted mirrors.

The output efficiency of the Yb:YAG was tested by replacing one of the high reflectivity mirrors with a 83% reflectivity output coupler. With this output coupler, and again using the prisms to separate the pump and signal light, we obtained the results shown in fig. 5. The expected slope efficiency can be estimated from the numerical results presented by Risk [11]. For the above experiment the ratio of reabsorption loss to the other cavity losses B is ~0.5, and the ratio of the pump to signal spot size, a, is taken as 1.5 (being ~1 in the guided plane and ~2 in the unguided plane). Inserting these values into the calculated data of ref. [11] we find that the efficiency

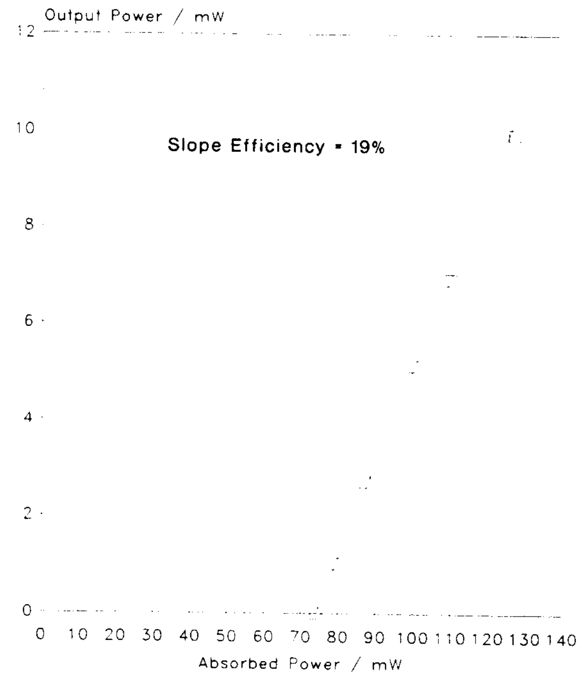

Fig. 5. Graph of waveguide laser output power versus absorbed pump power using an 83% reflectivity output coupler.

with which pump photons in excess of those required to reach threshold are converted to laser photons inside the cavity, dS/dF in the notation of ref. [11], is ~0.6. The output slope efficiency, η, is given by

$$\eta = \frac{T}{L+T} \frac{\nu_s}{\nu_p} \frac{dS}{dF}, \tag{2}$$

leading to a predicted slope efficiency of 0.3, somewhat greater than the actually observed value of 0.19.

The threshold results found for this rather lossy (2 dB/cm) planar waveguide are already similar to those found in the bulk laser experiments of ref. [1]. The main difference is in the lower slope efficiency, due to the extra propagation losses present in the waveguide. The prospects for channel waveguides made by ion-implantation therefore seem most promising. Based on the experience with Nd:YAG [6] threshold reductions of at least one order of magnitude can be expected due to the reduced spot sizes. Improved slope efficiencies are anticipated, both by using a higher transmission output mirror, and by reducing waveguide losses to values routinely achieved in Nd:YAG. Another route to improved performance could be via epitaxial growth of doped YAG where very low loss has been observed in planar waveguides [3,5] (~0.1 dB/cm). Techniques for fabricating channel waveguides from these epitaxial planar films are under investigation. If successful, then in principle very low threshold and high slope efficiency lasers could be achieved. The benefits of a waveguide geometry could then be extended to many other interesting quasi-three level laser systems such as the ~2 μm transitions in Ho^{3+} and Tm^{3+}, the ~1.6 μm transition in Er^{3+} and the ~0.95 μm transition in Nd^{3+}. Other transitions of a more purely three-level nature, not normally considered for bulk operation should also become viable in a waveguide geometry.

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