Low Threshold Quasi-Three-Level 946 nm Laser Operation of an Epitaxially Grown Nd:YAG Waveguide

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Abstract

We report the use of an epitaxially grown waveguide to achieve low threshold quasi-three level laser operation of Nd:YAG at 946nm.

Introduction

There has recently been much work on fabricating waveguide lasers based on crystal hosts by methods such as crystal fibre growth [1], ion-exchange [2], in-diffusion [3], ion-implantation [4], and epitaxial growth [5]. Despite the confinement of pump and signal beams to a few microns spot size, in general these lasers have not shown a clear advantage over bulk lasers in terms of thresholds due to propagation losses of the order of 0.1dB/cm or higher. Here we identify laser systems in which crystal waveguides will show great advantages over bulk lasers, namely 3 level and quasi-3 level transitions, and as an example describe the low threshold operation of a 946nm Nd:YAG epitaxial waveguide laser. The extra cavity loss arising from using a waveguide is less significant in (quasi-) three level systems as re-absorption loss from the lower laser level is present.

There has been much interest in the laser operation of the 946nm $^4F_{3/2}$-$^4I_{9/2}$ transition in Nd:YAG [6-8] as a means to obtaining a diode pumped blue laser source (after frequency doubling). One of the problems associated with this transition is that the lower laser level is the upper 857cm^{-1} crystal field component of the ground state manifold containing 0.7% of the population at room temperature. Here we report a waveguide laser that despite only having confinement in one direction and a laser transition which only has a relatively small percentage of the population in the lower laser level still shows thresholds lower than those achieved in equivalent bulk systems. The prospects for operation of other (quasi-) three level systems are also discussed.

Guide Properties

We have recently reported that Nd:YAG waveguides can be fabricated by liquid phase epitaxial growth of Nd:YAG layers on pure YAG substrates, followed by the growth of a pure YAG cladding layer [5]. Such waveguides exhibit very low loss for a crystal waveguide (≤0.05dB/cm) but rely purely on the Nd doping to achieve the refractive index difference required for guidance. In order to take full advantage of the waveguide geometry, guides of just a few microns width should be fabricated but this requires a larger index difference than can be produced by 1at.% Nd doping alone. The mixed crystal $Y_3(Al_{1-x}Ga_x)_5O_{12}$ is known to maintain the garnet crystal structure while having a controllably higher refractive index [9]. We report here for the first time the demonstration of a waveguide laser using the enhanced index difference caused by Ga doping. The waveguide described in this experiment has an active layer co-doped with 12at.% Ga, and 35at.% Lu (which compensates for the size mis-match between Ga and Al), increasing the refractive index difference to 1.4×10^{-2} (at 633nm). This guide has two modes for both TM and TE polarisations at 946nm with a calculated fundamental mode spot size ($1/e^2$ half-width of intensity) of 2.0μm.

The laser thresholds observed when operating Ga,Lu,Nd doped guides of various widths at 1.064μm indicated losses of 0.1-0.2 Db/cm, taking into account the fact that the stimulated emission cross-section at 1.064μm is reduced by a factor of two at this doping

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level [9]. Despite the somewhat increased propagation loss and the reduced stimulated emission cross-section, the fact that smaller spot sizes can be produced by these guides meant that the 1.064μm threshold for a 3.8μm width guide (propagation loss 0.15dB/cm) is similar to that found in the original waveguides [5] and that the expected threshold at 946nm is lower for these guides because the propagation loss is less significant for the quasi-three level system.

Results

For the experiment described here a cladded, 3.8μm active layer thickness guide was end polished to a length of 0.95mm to allow longitudinal pumping by an R6G dye laser at 588nm. This was slightly shorter than intended as only ~45% of the pump light was absorbed in a single pass. Thus the incident threshold power will not be the optimum value which would occur when the guide length was nearer to an absorption length. The laser cavity was formed by butting two thin light-weight mirrors against the polished end faces. These mirrors were held in place by the surface tension of a drop of fluorinated liquid although, in future, direct coating of the end faces would be preferred. The mirrors were highly reflecting at 946nm and had 81% transmission at 588nm. No attempt was made to feedback the unabsorbed pump light as we were interested in directly comparing our results to a similar experimental set up with bulk lasers [6]. The mirrors had ~95% transmission at 1.064μm to avoid oscillation at this wavelength. The pump light was end-launched using a X10 microscope objective forming a ~2μm circular waist at the input face.

Laser oscillation at 946nm was observed at a power incident on the input mirror of 4.0mW. Taking into account the mirror transmission and subtracting the pump power observed to emerge from the output end (due to less than 100% absorption and launch efficiency) we calculated an absorbed power threshold of 1.2mW. The output, observed with a CCD camera and image analyser (Big Sky Software Corporation beamview analyser), was single mode in both the guided and unguided planes with measured spot sizes of ~2μm and ~35μm respectively. This result compares favourably to the bulk laser result of Fan and Byer [6] who found an incident power threshold of ~5.7mW despite having a better optimised length crystal and using a more favourable pumping wavelength (808nm). Using the measured spot sizes and propagation loss, and using standard Nd:YAG material constants, we calculated an absorbed power threshold of 0.9mW. The small discrepancy between this value and the experimentally observed value of 1.2mW may be due to some reduction in the 946nm stimulated emission cross-section from that of standard Nd:YAG, as has been observed at 1.064μm [9]. The same calculations suggest that if channel waveguides could be fabricated, perhaps by ion-implanting low refractive index side walls or by etching, without greatly increasing the loss from the current level of 0.15dB/cm then thresholds of $<100\mu$W should be achieved. Further improvements could be made by choosing an output mirror that strongly reflects the unabsorbed pump light or using a cavity that resonates a single frequency pump source [8].

Conclusions

We have shown that waveguide geometries are highly suited to three-level and quasi-three-level laser transitions. Even for the 946nm transition in Nd:YAG, which has only 0.7% of the total population in the lower laser level, planar waveguides are seen to have advantages over bulk.

Another quasi-three-level laser is Yb:YAG, a potentially diode-pumpable, high power system without some of the limitations of Nd:YAG systems [10]. The 1.03μm laser transition in Yb:YAG terminates at 613cm^{-1} in the ground state manifold and has ~5% of the population in the lower laser level. Recently epitaxial waveguides with Yb(Ga,Lu):YAG active layers have been grown. Preliminary laser experiments with these waveguides have already shown very favourable results which will be discussed elsewhere.

The prospects for low threshold operation of waveguide lasers in other (quasi-) three level systems is also most promising. Well known transitions such as the ~2μm line of Ho^{3+} [11,12] and the ~1.6μm line of Er^{3+} [13] are equally promising, as are a number of other transitions not normally considered for bulk lasers because of their highly 3-level nature. The technique of epitaxial growth should also be extendable to different crystals enabling electro-optic and nonlinear effects to be used.

Waveguides are also suited to high power, diode pumped operation. This could be done by transverse pumping as has already been demonstrated in epitaxially grown Nd:YAG waveguides [14]. Here a planar waveguide geometry has the advantage of confining both the pump and laser in one dimension and has a good compatibility with the geometry of a diode bar. For end-pumped arrangements, clearly a channel geometry would be beneficial. This could be done by either ion-implanting low refractive index side walls or by etching side walls into the crystal.

References

1. M. J. F. Digonnet, C. J. Gaeta, D. O'Meara, and H. J. Shaw, IEEE J. Lightwave Technol.

LT-5, 642 (1987).
2. E. Lallier, J. P. Pochelle, M. Papuchon, M. P. De Micheli, M. J. Li, Q. He, D. B. Ostrowsky, C. Grezes-Besset, and E. Pelletier, IEEE J. Quantum Electron. **QE-27**, 618 (1991).
3. R. Brinkmann, W. Sohler, and H. Suche, Electron. Lett. **27**, 415 (1991).
4. S. J. Field, D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, P. J. Chandler, P. D. Townsend, and L. Zhang, Electron. Lett. **27**, 2375 (1991).
5. I. Chartier, B. Ferrand, D. Pelenc, S. J. Field, D. C. Hanna, A. C. Large, D. P. Shepherd, and A. C. Tropper, Opt. Lett. **17**, 810 (1992).
6. T. Y. Fan and R. L. Byer, Opt. Lett. **12**, 809 (1987).
7. W. P. Risk and W. Lenth, Opt. Lett. **12**, 993 (1987).
8. J. P. Cuthbertson and G. J. Dixon, Opt. Lett. **16**, 396 (1991).
9. R. K. Watts and W. C. Holton, J. Appl. Phys. **45**, 873 (1974).
10. P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, Opt. Lett. **16**, 1089 (1991).
11. R. Allen, L. Esterowitz, L. Goldberg, J. F. Weller, and M. Storm, Electron. Lett. **22**, 947 (1986).
12. T. Y. Fan, G. Huber, R. L. Byer, and P. Mitzscherlich, Opt. Lett. **12**, 678 (1987).
13. E. W. Duczynski, G. Huber, K. Petermann, and H. Strange, in Technical Digest of Topical Meeting on Tunable Solid State Lasers (Optical Society of America, Washington, D.C., 1987), p.197.
14. D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, I. Chartier, B. Ferrand, and D. Pelenc, Opt. Comm. **91**, 229 (1992).