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**Low Threshold Quasi-Three-Level 946nm Laser Operation of an Epitaxially Grown
Nd:Y₃Al₅O₁₂ Waveguide**

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Abstract

We report the 946nm laser operation of an epitaxially grown Nd:YAG planar waveguide. The incident and absorbed power thresholds of 4mW and 1.2mW respectively are lower than those reported for bulk lasers when using a similar experimental set up. We also report the use of Ga doping of the active layer to increase the refractive index difference to allow the production of very small guiding layers.

There has been much interest in the laser operation of the 946nm ${}^4F_{3/2}$ - ${}^4I_{9/2}$ transition in Nd:Y₃Al₅O₁₂ (Nd:YAG)¹⁻⁵ as a means to obtaining a diode-pumped blue laser source (via frequency doubling). A drawback with this transition is that the lower laser level (the upper Stark component of the ground manifold, 857cm⁻¹ above the ground state) contains a significant population, 0.7% of the total Nd³⁺ population, at room temperature. This leads to absorption loss at the laser wavelength, which consequently increases the threshold pump intensity. This increased threshold pump power requirement can be mitigated by using a waveguide geometry⁶, to confine the pump and laser radiation, so that the required intensity is reached with a modest pump power. In the case of Nd:YAG, various methods for forming waveguides have been demonstrated⁷⁻¹⁰. Typically the waveguides so fabricated introduce additional loss over that of the bulk material. However, in the presence of lower level absorption loss, the additional propagation loss of the waveguide can be relatively insignificant and waveguide lasers based on three-level and quasi-three level systems are therefore able, in principle, to show significantly lower thresholds than their bulk counterparts. In confirmation of this principle, we report here a waveguide laser that, despite having confinement in only one direction and a laser transition which only has a very small percentage of the population in the lower laser level, still shows thresholds lower than those achieved in equivalent bulk systems. With guidance in both dimensions and a more pronounced three-level nature the threshold improvement over bulk performance will be more dramatic. The prospects for improved performance from some other (quasi-) three-level systems are also discussed.

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 layer⁹. Such waveguides have exhibited extremely low loss ($\leq 0.05\text{dB/cm}$) 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 are ideally required but this in turn requires a larger index difference than can be produced by 1at.% Nd doping alone, (measured to be 0.48×10^{-3}). Gallium garnets are known to have higher refractive indices than aluminium garnets and can be grown by liquid-phase epitaxy, provided that the film-substrate lattice mismatch is low¹¹. Therefore we have grown gallium doped layers and studied the film-substrate refractive index difference for various dopant concentrations. The results of this study will be reported and discussed elsewhere¹². The waveguide described in this experiment was chosen to have an active layer co-doped with 12at.% Ga, and 35at.% Lu (which compensates for the size mismatch 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 $2.0\mu\text{m}$.

The spectroscopic characteristics in the 940nm region of this Ga,Lu,Nd doped YAG were compared to that of bulk Nd:YAG and Nd:YAG epitaxial layers. Luminescence lifetime measurements yielded the same value (within experimental error) of $240 \pm 20\mu\text{s}$ for the three materials, in agreement with the usual value for bulk Nd:YAG. Emission spectra were recorded under R6G dye laser excitation and are shown in fig.1. Ga,Lu,Nd doped YAG, (a), exhibits broader emission lines than bulk Nd:YAG, (c). The epitaxial Nd:YAG spectrum, (b), proves that this broadening is not due to the growth technique but to the material itself. Moreover, this broadening has already been observed in ref.13 for bulk Ga,Nd doped YAG at $1.064\mu\text{m}$, leading to a decrease in the emission cross-section by a

factor of two. We have determined the effects of Ga doping on the emission cross-section σ_e at 946nm. Using the values found in ref.14, for Nd:YAG σ_e is $5.3 \times 10^{-24} \text{m}^2$ and is given by¹⁴,

$$\sigma_e = \frac{\eta \lambda_p^5}{\tau_f \left(\int \lambda I(\lambda) d\lambda \right) f 8\pi n^2 c} I(\lambda_p) \quad (1)$$

where $I(\lambda)$ is the spectral fluorescence intensity, τ_f is the fluorescence lifetime of the ${}^4F_{3/2}$ state, η is the radiative quantum efficiency of the upper level, f is the fraction of the excited population in the upper state of the considered transition, n is the refractive index, and λ_p is the peak emission wavelength. Considering that n , η , f , and λ_p are nearly equal for Nd:Ga:Lu:YAG and Nd:YAG and that $I(\lambda)$ has a lorentzian lineshape, the ratio between the stimulated emission cross-section of the two materials reduces to,

$$\frac{\sigma_{e \text{ Nd:Ga:Lu:YAG}}(946\text{nm})}{\sigma_{e \text{ Nd:YAG}}(946\text{nm})} = \frac{\Delta \nu_{\text{Nd:YAG}}}{\Delta \nu_{\text{Nd:Lu:Ga:YAG}}} \quad (2)$$

where $\Delta \nu$ is the luminescence linewidth for each material. The ratio of the linewidths was 0.58 and so we obtain $\sigma_e(946\text{nm}) = 3.1 \times 10^{-24} \text{m}^2$.

The laser thresholds observed when operating Ga,Lu,Nd doped guides of various widths at $1.064\mu\text{m}$ indicated losses of 0.1-0.2 dB/cm, after taking into account the fact that the stimulated emission cross-section at $1.064\mu\text{m}$ is reduced by a factor of two at this doping level¹³. Despite the increased propagation loss and the reduced stimulated emission cross-section, the fact that smaller spot sizes can be produced by the Ga doped guides meant that the $1.064\mu\text{m}$ laser threshold for a $3.8\mu\text{m}$ width guide (propagation loss 0.15dB/cm) was similar to the submilliwatt thresholds found in the original waveguides⁹, while the expected threshold at 946nm is lower because the propagation loss is less significant for this quasi-three level system, (for which the bulk absorption loss is 0.17dB/cm).

For the experiment described here a cladded guide having a $3.8\mu\text{m}$ thick active layer was end polished to a length of 0.95mm to allow longitudinal pumping by an R6G dye laser at 588nm, see fig.2. This was slightly shorter than ideal as it was found that only $\sim 45\%$ 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 is roughly one 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 feed back the unabsorbed pump light as we were interested in directly comparing our results to a similar experimental set up that had been used with bulk lasers¹. The mirrors had $\sim 95\%$ transmission at $1.064\mu\text{m}$ to avoid oscillation at this wavelength. The pump light was end-launched using a X10 microscope objective forming a $\sim 2\mu\text{m}$ 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 $\sim 2\mu\text{m}$ and $\sim 35\mu\text{m}$ respectively. This result compares favourably to the bulk laser result of Fan and Byer¹ who found an incident power threshold of $\sim 5.7\text{mW}$ despite having a more optimum length crystal and using a more favourable pumping wavelength (808nm). The theoretical absorbed pump power is given by the expression²,

$$P_{th,abs} = \frac{\pi \hbar \nu_p}{4 \sigma_a f \tau_f} (W_{px}^2 + W_{sx}^2)^{1/2} (W_{py}^2 + W_{sy}^2)^{1/2} (L + T + 2N_1^0 \sigma_a l) \quad (3)$$

where N_1^0 is the equilibrium population density of the lower laser level ($1 \times 10^{24} \text{m}^{-3}$), W is the $1/e^2$ beam radius for the pump (p) and signal (s) in the guided (y) and unguided (x) directions (averaged over the cavity length), ν_p is the pump frequency, τ_f is the upper-state lifetime ($240\mu\text{s}$), l is the crystal length, L is the fixed cavity round trip loss, T is the output coupling, and f is the fraction of the total ${}^4F_{3/2}$ population that resides in the lower Stark component of the ${}^4F_{3/2}$ doublet (~ 0.6 at room temperature). The absorption cross-section at 946nm, σ_a , has been found to be different from the emission cross-section due to vibronic interactions¹⁴ and has a value of $4 \times 10^{-24} \text{m}^2$ for Nd:YAG. If we assume a similar reduction in σ_a to that found in σ_e in Ga:Lu:Nd:YAG then we can use $\sigma_a = 2.3 \times 10^{-24} \text{m}^2$. Putting our experimental

values into eqn.3 ($W_{py} \approx W_{sy} = 2\mu\text{m}$, $W_{sx} = 35\mu\text{m}$, $W_{px} = 30\mu\text{m}$, $l = 0.95\text{mm}$, $L = 0.0066$, $T = 0$) we predict an absorbed power threshold of 0.9mW. The agreement between this value and the experimentally observed value of 1.2mW is good taking into account the uncertainty in some of the values used. From eqn.3 we can see that if channel waveguides could be fabricated, for example by ion-implanting low refractive index side walls or by etching, without dramatically increasing the loss from the current level of 0.15dB/cm then thresholds of $< 100\mu\text{W}$ should be achievable. Further improvements could be made by choosing an output mirror that strongly reflects the unabsorbed pump light or, but at some expense in complexity, by using a shorter length of crystal and a cavity that resonates a single frequency pump source, as has been reported^{4,5}.

Unfortunately we were unable to test the output efficiency of this laser due to a lack of suitable mirrors. However predictions based on the theory of Risk¹⁵ for diode pumping with a 5% output coupler suggest that slope efficiencies of $\sim 60\%$ with respect to absorbed power could be achieved for an increase in threshold to just $\sim 5\text{mW}$. These favourable performance predictions are the consequence of a high value for $T/(L+T)$ (~ 0.9), the closely matched pump and signal wavelengths ($\nu_s/\nu_p \sim 0.85$), and the high efficiency (~ 0.85) with which absorbed pump photons could be converted to laser photons due to the low ratio of reabsorption losses to output coupling losses and the possibility of good overlap of the pump and signal modes. The latter would be especially favourable in a channel waveguide for which we would still predict submilliwatt thresholds using the above output coupling.

The prospects for low threshold operation of waveguide lasers in other (quasi-) three level system is also most promising. For example the $1.03\mu\text{m}$ laser transition in Yb:YAG

terminates at 613cm^{-1} in the ground state manifold and has $\sim 5\%$ of the population in the lower laser level. Using the material constants quoted in ref.16 and similar spot sizes and losses to the guide used in this experiment we would predict an absorbed power threshold of $\sim 4\text{mW}$ for a 1.65mm long crystal and a 10% output coupler. This corresponds to an experimentally observed bulk laser threshold of 71mW ¹⁶. Other well known transitions such as the $\sim 2\mu\text{m}$ line of Ho^{3+} ^{17,18} and the $\sim 1.6\mu\text{m}$ of Er^{3+} ¹⁹ appear equally promising in a waveguide geometry. Other transitions not normally considered for bulk lasers because of their highly 3-level nature, such as transitions to the lower lying levels of the ground state manifold in Nd^{3+} (900nm to 869nm) would show enormous advantages from going to a waveguide geometry.

In conclusion we have demonstrated that waveguide geometries can give a clear advantage over bulk lasers in terms of laser threshold, particularly for transitions with large populations in the lower laser level. Here we have shown that even when using a planar guide we see lower thresholds than obtained in equivalent bulk laser systems for a transition that has only 0.7% of the population in the lower laser level. The prospects for very low threshold waveguide laser operation of other (quasi-) three level systems therefore seem very promising, with typically a further order of magnitude improvement possible if channel guides could be fabricated without substantially increasing the current propagation losses. Various channel fabrication methods are currently under investigation.

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References

1. T. Y. Fan and R. L. Byer, *Opt. Lett.* **12**, 809 (1987).
2. W. P. Risk and W. Lenth, *Opt. Lett.* **12**, 993 (1987).
3. T. Y. Fan and R. L. Byer, *IEEE J. Quantum Electron.* **QE-23**, 605 (1987).
4. J. P. Cuthbertson and G. J. Dixon, *Opt. Lett.* **16**, 396 (1991).
5. W. J. Kozlovsky and W. P. Risk, *IEEE J. Quantum Electron.* **QE-28**, 1139 (1992).
6. I. P. Alcock, A. I. Ferguson, D. C. Hanna, and A. C. Tropper, *Opt. Lett.* **11**, 709 (1986).
7. M. J. F. Digonnet, C. J. Gaeta, D. O'Meara, and H. J. Shaw, *IEEE J. Lightwave Technol.* **LT-5**, 642 (1987).
8. 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).
9. 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).
10. D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, I. Chartier, B. Ferrand, and D. Pelenc, *Opt. Commun.* **91**, 229 (1992).
11. P.K.Tien, R.J.Martin, S.L.Blank, S.W.Wemple, and L.J.Varnerin, *Appl. Phys. Lett.* **21**, 207 (1972).
12. D.Pelenc and J.C.Vial, unpublished.
13. R. K. Watts and W. C. Holton, *J. Appl. Phys.* **45**, 873 (1974).
14. B. F. Aull and H. P. Jenssen, *IEEE J. Quantum Electron.* **QE-18**, 925 (1982).
15. W. P. Risk, *J. Opt. Soc. Am. B* **5**, 1412 (1988).
16. P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, *Opt. Lett.* **16**, 1089 (1991).

17. R. Allen, L. Esterowitz, L. Goldberg, J. F. Weller, and M. Storm, *Electron. Lett.* **22**, 947 (1986).
18. T. Y. Fan, G. Huber, R. L. Byer, and P. Mitzscherlich, *Opt. Lett.* **12**, 678 (1987).
19. E. W. Duczynski, G. Huber, K. Petermann, and H. Strange, in *Digest of Topical Meeting on Tunable Solid State Lasers* (Optical Society of America, Washington, D.C., 1987), p.197.

Figure Captions

Figure 1 Fluorescence spectra of Ga:Lu:Nd:YAG (a) and Nd:YAG (b) epitaxial waveguides, and of bulk Nd:YAG (c) around 940nm.

Figure 2 Schematic side view of the experimental set up used to investigate the 946nm laser performance of the epitaxially grown Ga:Lu:Nd:YAG waveguide laser. The cavity is formed by the two plane mirrors M_1 and M_2 .



