Low threshold quasi-three-level 946 nm laser operation of an epitaxially grown Nd:$Y_3Al_5O_{12}$ waveguide

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We report the 946 nm laser operation of an epitaxially grown Nd:YAG planar waveguide. The incident and absorbed power thresholds of 4 and 1.2 mW, respectively, are lower than those reported for bulk lasers when using a similar experimental setup. 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 946 nm $^4F_{3/2}$-$^4I_{9/2}$ transition in Nd:$Y_3Al_5O_{12}$ (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, 857 cm^{-1} above the ground state) contains a significant population, 0.7% of the total Nd^{3+} 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 geometry,[6] 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 demonstrated.[7-10] 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 that 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 layer.[9] Such waveguides have exhibited extremely low loss (<0.05 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 micrometers width are ideally required but this in turn requires a larger index difference than can be produced by 1 at. % Nd doping alone (measured to be 0.48×10^{-3}). Gallium garnets are known to have higher refractive indices than aluminum garnets and can be grown by liquid-phase epitaxy, provided that the film-substrate lattice mismatch is low.[11] 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 elsewhere.[12] The waveguide described in this experiment was chosen to have an active layer codoped with 12 at. % Ga. and 35 at. % Lu (which compensates for the size mismatch between Ga and Al), increasing the refractive index difference to 1.4×10^{-2} (at 633 nm). This guide has two modes for both transverse-magnetic (TM) and transverse-electric (TE) polarizations at 946 nm with a calculated fundamental mode spot size ($1/e^2$ half-width of intensity) of 2.0 μm.

The spectroscopic characteristics in the 940 nm 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±20 μs 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 μm, leading to a decrease in the emission cross section by a factor of 2. We have determined the effects of Ga doping on the emission cross section σ_e at 946 nm. Using the values found in Ref. 14, for Nd:YAG σ_e is 5.3×10^{-24} m^2 and is given by[14]

$$\sigma_e=\frac{\eta\lambda_p^5}{\tau_f(\int\lambda I(\lambda)d\lambda)f8\pi n^2c}I(\lambda_p), \qquad (1)$$

where $I(\lambda)$ is the spectral fluorescence intensity, τ_f is the fluorescence lifetime of the $^4F_{3/2}$ state, η is the radiative

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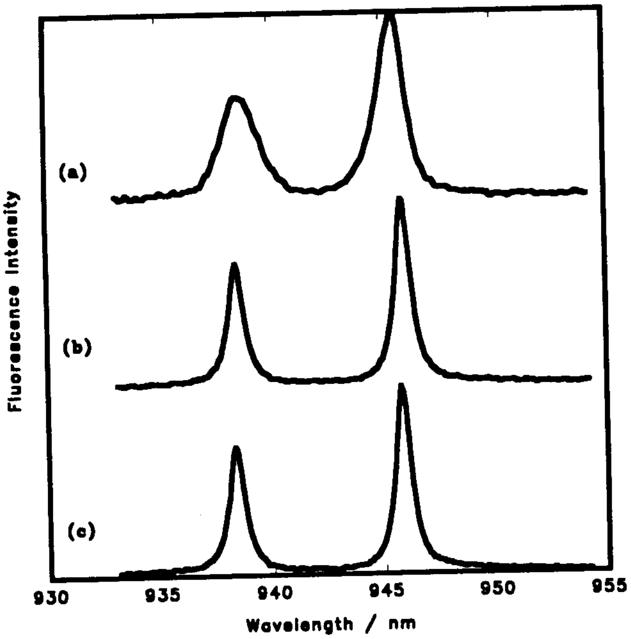

FIG. 1. Fluorescence spectra of Ga:Lu:Nd:YAG (a) and Nd:YAG (b) epitaxial waveguides, and of bulk Nd:YAG (c) around 940 nm.

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 line shape, the ratio between the stimulated emission cross section of the two materials reduces to

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

where $\Delta\nu$ is the luminescence linewidth for each material. The ratio of the linewidths was 0.58 and so we obtain σ_e (946 nm) $=3.1\times10^{-24}$ m^2.

The laser thresholds observed when operating Ga-, Lu-, and Nd-doped guides of various widths at 1.064 μm indicated losses of 0.1-0.2 dB/cm, after taking into account the fact that the stimulated emission cross section at 1.064 μm is reduced by a factor of two at this doping level.[13] 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 μm laser threshold for a 3.8 μm width guide (propagation loss 0.15 dB/cm) was similar to the submilliwatt thresholds found in the original waveguides,[9] while the expected threshold at 946 nm is lower because the propagation loss is less significant for this quasi-three-level system (for which the bulk absorption loss is 0.17 dB/cm).

For the experiment described here a cladded guide having a 3.8 μm thick active layer was end polished to a length of 0.95 mm to allow longitudinal pumping by an R6G dye laser at 588 nm (see Fig. 2). This was slightly shorter than ideal as it was found that only ~45% of the pump light was absorbed in a single pass. Thus, the incident threshold power will not be the optimum value that 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 the future, direct coating of the end faces would be preferred. The mirrors were highly reflecting at 946 nm and had 81% transmission at 588 nm. No attempt was made to feed back the unabsorbed pump light as we were interested in directly comparing our results to a similar experimental setup that had been used with bulk lasers.[1] The mirrors had ~95% transmission at 1.064 μm to avoid oscillation at this wavelength. The pump light was end-launched using a X10 microscope objective forming a ~2 μm circular waist at the input face.

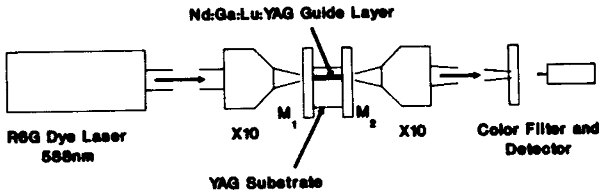

FIG. 2. Schematic side view of the experimental set up used to investigate the 946 nm laser performance of the epitaxially grown Ga:Lu:Nd:YAG waveguide laser. The cavity is formed by the two plane mirrors M_1 and M_2.

Laser oscillation at 946 nm was observed at a power incident on the input mirror of 4.0 mW. 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 1.2 mW. The output, observed with a CCD camera and image analyzer (Big Sky Software Corporation beamview analyzer), was single mode in both the guided and unguided planes with measured spot sizes of ~2 and ~35 μm, respectively. This result compares favorably to the bulk laser result of Fan and Byer[1] who found an incident power threshold of ~5.7 mW despite having a more optimum length crystal and using a more favorable pumping wavelength (808 nm). The theoretical absorbed pump power is given by the expression[2]

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

where N_1^0 is the equilibrium population density of the lower laser level (1×10^{24} 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 upperstate lifetime (240 μs), 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 946 nm, σ_a, has been found to be different from the emission cross section due to vibronic interactions[14] and has a value of 4×10^{-24} 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 $\sigma_a=2.3\times10^{-24}$ m^2. Putting our experimental values into Eq. (3) ($W_{py}\approx W_{sy}=2\mu$m, $W_{sx}=35$ μm, $W_{px}=30$ μm, $l=0.95$ mm, $L=0.0066$, $T=0$) we predict an absorbed power threshold of 0.9 mW. The agreement between this value and the experimentally observed value of 1.2 mW is good taking into account the uncertainty in some of the values used. From Eq. (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 0.15 dB/cm then thresholds of < 100 μW 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 Risk[15] for diode pumping with a 5% output coupler suggest that slope efficiencies of ~60% with respect to absorbed power could be achieved for an increase in threshold to just ~5 mW. These favorable performance predictions are the consequence of a high value for $T/(L+T)$ (~0.9), the closely matched pump and signal wavelengths ($v_s/v_p\sim0.85$), 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 favorable 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 μm laser transition in Yb:YAG terminates at 613 cm^{-1} in the ground state manifold and has ~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 ~4 mW for a 1.65 mm long crystal and a 10% output coupler. This corresponds to an experimentally observed bulk laser threshold of 71 mW.[16] Other well known transitions such as the ~2 μm line of Ho^{3+} (Refs. 17 and 18) and the ~1.6 μm of Er^{3+} (Ref. 19) appear equally promising in a waveguide geometry. Other transitions not normally considered for bulk lasers because of their highly three-level nature, such as transitions to the lower lying levels of the ground state manifold in Nd^{3+} (900–869 nm) 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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