Growth and low-threshold laser oscillation of an epitaxially grown Nd:YAG waveguide

I. Chartier, B. Ferrand, and D. Pelenc

Laboratoire d'Electronique de Technologie et d'Instrumentation, Département Optonique, Commissariat à l'Energie Atomique, Centre d'Etudes Nucleaires de Grenoble, 85X 38041 Grenoble Cedex, France

S. J. Field, D. C. Hanna, A. C. Large, D. P. Shepherd, and A. C. Tropper

Department of Physics and Optoelectronics Research Centre, University of Southampton, Highfield, Southampton SO9 5NH, UK

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We report 1.064-μm laser operation of an epitaxially grown Nd:YAG planar waveguide with thresholds as low as ~0.7 mW when high-reflectivity mirrors are used. The output is single mode and, when a 83% reflectivity output coupler is used, has a diode pumped slope efficiency of ~40%. Output powers in excess of 60 mW have been obtained when pumping with a Rhodamine 6G dye laser.

The confinement of light in optical waveguides allows a small spot size and hence a high intensity to be maintained over lengths longer than would normally be allowed by diffraction. If the waveguide is doped with an active laser ion, then extremely low laser thresholds (and extremely high amplifications per unit pump power) can be achieved if the waveguide loss is low. Such behavior has been successfully demonstrated in glass optical fibers, and recently much research has been carried on crystal host waveguide lasers. Successful experiments in growing Nd:YAG by liquid-phase epitaxy have already been reported, and laser emission has been demonstrated.

Here we report the fabrication and laser operation of a new epitaxially grown laser waveguide made of a Nd:YAG active layer and a pure YAG cladding layer. In this waveguide a laser threshold of ~0.7 mW was measured. This value is one of the lowest obtained for crystal waveguide lasers and is indicative of a very small waveguide loss, estimated to be ≤0.05 dB/cm. With the possibility of doping various alternative laser ions (e.g., Er³⁺, Tm³⁺, and Cr³⁺) into the YAG host, there appears to be considerable scope for development of a range of efficient lasers and amplifiers.

A planar waveguide laser can be realized with a thin active layer deposited onto a lower refractive-index substrate (this is the case of Nd:YAG on YAG). The fabrication of such a waveguide requires a high degree of perfection in the polishing of the end faces and a good sharpness of the edges of the active layer. Such requirements are met more easily if the active layer is protected by a cladding material. A cladding layer may also help to reduce scattering losses from the top surface by reducing the refractive-index difference at this boundary.

We have fabricated a new Nd:YAG waveguide in which the active layer is protected by a pure YAG layer, both grown by liquid-phase epitaxy on a YAG substrate.
Using a nominally 83% reflectivity output coupler, we found an output slope efficiency of ~30% with respect to launched power, with an output power of 61 mW for the maximum available 250 mW of launched power. The threshold rises to 1.8 mW by using this output coupler. The value of 30% is a lower limit as we are again assuming 100% launch efficiency. The polarization of the output was observed to vary slowly from a mixture of TE and TM to a single linear polarization and back, possibly owing to thermal effects.

Diode-pumped operation has also been demonstrated by using a single-mode 100-mW GaAlAs diode laser (Spectra Diode Laboratories SDL-5412-H1). The output from this laser was collimated and then focused to an ~10-μm waist at the waveguide end face. With two high-reflectivity mirrors a threshold of 1.3 mW was obtained. In theory the threshold should be lower than for 590-nm pumping since the pump photons are less energetic. It is possible that the higher threshold is simply due to slightly worse butting of the mirrors in this case, since the low propagation loss has the consequence that the threshold is sensitive to other sources of loss. Direct coating of the end faces would solve this problem. Using a nominally 83% reflectivity output coupler, we observed the results shown in Fig. 1. A best fit to the experimental points gives a slope efficiency with respect to launched power (assuming 100% launch efficiency) of 40 ± 3%, which, as expected with a longer-wavelength pump, is better than that observed with dye laser pumping. The threshold of ~14 mW is consistent with the losses being dominated by the mirror transmission.

In conclusion, epitaxial growth of Nd:YAG has been used to form a waveguide laser. The low threshold obtained (~0.7 mW) indicates very low propagation losses (~0.05 dB/cm). Dye-laser and diode pumping have been demonstrated, and a slope efficiency of ~40% has been observed. In order to improve the waveguide performances, direct coating of the end faces, optimization of the guide depth, and index difference enhancement by Ga substitution are in progress. Production of channel waveguides, possibly by etching techniques, could also give considerable improvement if the low loss can be maintained. As there are many alternative laser transitions for Nd:YAG doped with Nd³⁺ and many alternative dopants, such as Er³⁺, Tm³⁺, and Cr³⁺, it is clear that potentially a wide range of different lasers could benefit from this epitaxial waveguiding arrangement. Since the epitaxial growth technique should be widely applicable to other host crystals, the scope for development is extremely wide indeed.

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