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

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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,[1] and recently much research has been carried out on crystal host waveguide lasers.[2-5] Successful experiments in growing Nd:YAG by liquid-phase epitaxy have already been reported, and laser emission has been demonstrated.[6-8]

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., Er^{3+}, Tm^{3+}, and Cr^{4+}) 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.[9-11] 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.

The Nd-doped active layer was first grown from a PbO/B_2O_3 flux. The melt composition consisted of a mixture of $PbO/B_2O_3/Al_2O_3/Y_2O_3/Nd_2O_3$ in concentrations of 89.9/7.4/2.3/0.3/0.1 mol.%, respectively.[9] The active layer was grown by horizontally dipping the YAG substrate into this melt at a temperature of approximately 1000°C. This active layer was then dipped into a new melt with roughly the same composition but without Nd in order that the cladding layer could be grown.

Typical layer thicknesses are in the range of 10–50 μm and 50–100 μm for the active layers and the cladding layers, respectively. The thickness was determined by weighing the sample before and after the growth or by observation of the end face by optical microscopy. The composition of the active layer was either estimated by lattice mismatch measurements or by x-ray microprobe analysis. The surface morphology and quality were examined by optical microscopy after each growth.

For the results described here, we used a waveguide made of a 38-μm-thick active layer doped with 1.5 at.% Nd and a 60-μm-thick pure YAG cladding layer. The crystal was 6 mm long with parallel polished end faces. The laser cavity was formed by butting plane dielectric mirrors directly onto the polished end faces. These lightweight mirrors were held in place by the surface tension of a drop of fluorinated liquid. Initial tests were carried out by using a Rhodamine 6G dye laser as the pump source, tuned to the strong Nd^{3+} absorption near 590 nm. The light was coupled into the guide with a 5-cm focal-length lens to produce an ~10-μm waist spot size ($1/e^2$ half-width of intensity) at the waveguide end face. Using high-reflectivity mirrors, we obtained a threshold pump power of 0.95 mW incident upon the 5-cm lens. This corresponds to 0.67 mW in the waveguide, accounting for the lens and mirror transmissions and assuming a 100% launch efficiency. The 6-mm-long waveguide absorbs virtually all of this light.

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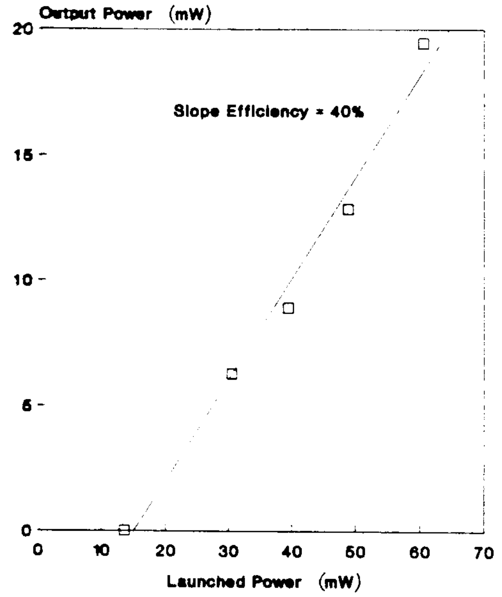

Fig. 1. Output power versus launched power for a diode-pumped Nd:YAG planar waveguide.

The output and pump mode profiles were observed by focusing the output onto a CCD camera and analyzer (Big Sky Software Corporation beamview analyzer). From the measured waist sizes on the camera the mode size could be calculated, which gave a vertical (guided) spot size of 14 μm. This implies that the mode is well contained within the physical dimensions of the Nd:YAG layer. Using the quoted values of refractive index for undoped YAG (1.81523) and 1 at.% Nd-doped YAG (1.81633),[12] we predict a fundamental mode spot size of 16.5 μm. The difference between the experimental and calculated figures may be due to the slightly higher doping level or to strain imposed by the epitaxial growth of Nd:YAG on undoped YAG, which gives a higher than expected index difference. The horizontal (unguided) spot size is 4.3 times larger at 60 μm. Lasing could occur with either a single- or double-lobed output, but optimum alignment always led to lasing on just the fundamental mode. The 590-nm pump appears to propagate in a higher-order mode with a three-lobed output.

The theoretical absorbed power threshold is given by[13]

$$P = \frac{\pi h\nu}{2\sigma\tau_{\mathrm{fl}}}(W_{px}^2 + W_{sx}^2)^{1/2}(W_{py}^2 + W_{sy}^2)^{1/2}L, \qquad (1)$$

where σ is the emission cross section (3.5×10^{-23} m^2), τ_{fl} is the fluorescence lifetime (230 μs), W is the averaged spot size for the pump (p) and signal (s) in the vertical (y) and horizontal (x) dimensions, and L is the single-pass exponential loss. We can find an upper limit for the propagation loss by assuming that the pump has similar spot sizes to the signal and that the mirror butting is lossless. This gives $L = 0.006$, which implies a less than 0.05-dB/cm propagation loss, which is less than the best losses obtained for Nd:YAG crystal fibers[5] and approaches that of bulk Nd:YAG.[14]

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 18 mW by using this output coupler. The value of 30% is a lower limit as we are again assuming a 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 ($\leq$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 planar 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 YAG doped with Nd^{3+} and many alternative dopants, such as Er^{3+}, Tm^{3+}, and Cr^{4+}, 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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