A low threshold, room temperature 1.64 μm Yb:Er:$Y_3Al_5O_{12}$ waveguide laser

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(Received 11 May 1994; accepted for publication 10 August 1994)

Room temperature 1.64 μm laser operation of Yb:Er:$Y_3Al_5O_{12}$ has been achieved using a planar waveguide grown by liquid phase epitaxy. A comparatively low threshold of 17 mW was achieved for this transition indicating low waveguide propagation loss for this material and suggesting good prospects for low threshold 3 μm and upconversion visible lasers based on this system.

The 1.6 μm $^4I_{13/2}$ to $^4I_{15/2}$ transition in Er:$Y_3Al_5O_{12}$ (Er:YAG) is of interest in that it could provide a convenient eye-safe laser for which there are many possible uses. Operation of this quasi-3-level laser scheme in Er^{3+} doped YAG has been demonstrated by several authors.[1-3] Co-doping with Yb^{3+} should allow efficient InGaAs diode pumping via the strong and broad absorptions around 940 and 970 nm,[4,5] provided there is an efficient energy transfer between the Yb^{3+} and Er^{3+} ions. Flash-lamp pumping of the Yb:Er:YAG system was demonstrated by White and Schleusener,[6] and recently laser pumping has been demonstrated by Kubo and Kane.[7] However the laser threshold was high and the slope efficiency very low, apparently due to strong upconversion which results in fluorescence at ~3 μm from the $^4I_{11/2}$ to $^4I_{13/2}$ transition and at ~550 nm from the $^4S_{3/2}$ to $^4I_{15/2}$ transition. Both these transitions have been made to lase in Er^{3+} doped YAG[8,9] (at 2.94 μm and 561 nm, respectively) and have potential interest for medical applications and as diode-pumped visible sources, respectively. Upconversion processes have been noted to be even stronger in Yb:Er:YAG[10] than in the singly doped material. Motivated by the many interesting laser transitions available from this system we have investigated the preparation of Yb:Er:YAG in the form of epitaxially grown thin films. Thin YAG films have previously been fabricated by liquid-phase epitaxial growth with Nd^{3+} and Yb^{3+} doping.[5,11] They have shown very low thresholds as planar waveguide lasers (~0.7 and ~11 mW, respectively), indicating very low propagation losses of <0.1 dB/cm. The use of such guides with Er^{3+} doped YAG should enable lower lasing thresholds to be achieved than in bulk material with the possibility of a further order of magnitude reduction once channel waveguides can be produced based on these planar thin films. With these longer term goals in mind we have initially chosen to investigate laser action of the quasi-three level 1.6 μm line as a test of the waveguide quality.

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For the 1.6 μm laser tests three waveguides with the dimensions shown in Table I were grown. The liquid-phase epitaxial growth fabrication method is similar to that described in Ref. 13. The waveguides consisted of a pure YAG substrate, a doped YAG active layer, and a pure YAG cladding layer. All the samples had active layers of YAG doped with Ga (4 at.%), Lu (<1 at.%), Yb (6 at.%), and Er (~0.5 at.%). Ga doping is used to control the refractive index in the active region while the Lu compensates for the size mismatch between Ga and Al. At this doping level an index difference of $\sim 5\times 10^{-3}$ is achieved between the YAG substrate and doped layer. Table I shows the calculated mode spot sizes ($1/e^2$ intensity radius) for the three waveguides tested. It can be seen that the index difference is enough to allow a well-confined mode for guide depths of down to ~10 μm. In shallower guides a significant proportion of the mode would propagate in the cladding and substrate regions. The Er doping level is estimated to be ~0.5 at.%, but is not precisely known because this is at the detection limit of the x-ray analysis used to measure the concentrations. The Yb-Er transfer efficiency should be between the values of 18% and 66% reported in Ref. 11 for Er doping levels of 0.1 and 1 at.%, respectively, with a similar Yb doping level (6.5 at.%). The lifetime of the 1.6 μm fluorescence was measured to be 4 ms and the emission spectrum is shown in Fig. 1. The fluorescence spectrum around the 550 nm region from the $^4S_{3/2}$ level is shown in Fig. 2.

Waveguides always introduce extra propagation losses compared to similar bulk materials. In the case of epitaxially grown YAG planar waveguides, losses of ~0.1 dB/cm have been found experimentally.[11,13] For the 1.6 μm transition of Er doped YAG this waveguide propagation loss disadvantage is offset by the fact that there is an absorption loss at the laser waveguide for both waveguide and bulk due to the quasi-three level nature of the transition. The lower laser level, in the Stark split ground manifold, is 526 cm^{-1} above the ground level and contains ~2% of the total Er population.

 0021-8979/94/76(11)/7651/3/$6.00

TABLE I. Waveguide dimensions.

Cladding layer (depth/μm)	Active layer (depth/μm)	Calculated number of modes at 1.64 μm	Calculated fundamental mode spot size, W_y/μm
18	18	3	8.4
24	10	2	5.4
20	6.8	2	4.5

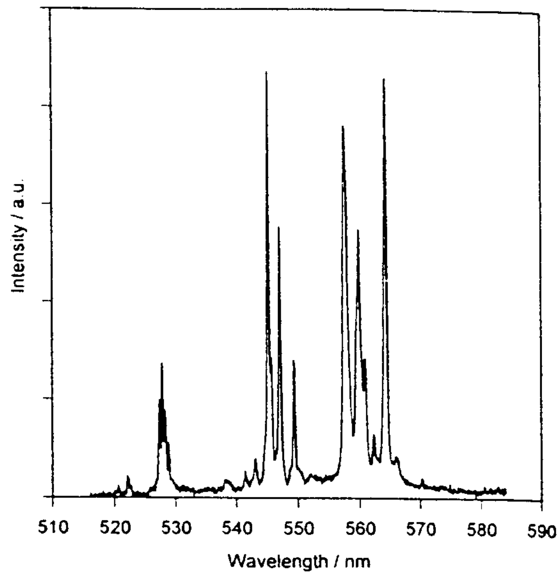

FIG. 2. Emission spectrum of the Yb:Er:YAG epitaxial waveguide around 550 nm.

The experimental arrangement used to investigate the laser performance of these guides is shown in Fig. 3. A $Ti:Al_2O_3$ laser was used to simulate diode laser pumping on the strong Yb absorption at 968 nm. The waveguides were cut and polished to a length of 1.8 mm, approximately equal to one absorption length at the pump wavelength. Launch efficiency into the guides was optimized by choosing the appropriate microscope objective for any particular guide. The resonator was formed by butt-coupling two thin light-weight mirrors to the polished ends of the waveguide, these mirrors being held in place by the surface tension of a drop of fluorinated liquid.[14] This arrangement makes it easy for mirrors to be changed, as required when investigating the effect of varying the output coupler transmission. The output light is collected with another objective and focused onto a germanium detector through color filters which cut out light of shorter wavelength than 1.1 μm.

Using mirrors having high reflectivity at 1.64 μm and 96% transmission at the pump wavelength (measured when placed against YAG with fluorinated liquid) we obtained continuous wave laser action in all three waveguides tested. The lowest threshold was found using the guide whose active layer had a width of 10 μm. From Table I we can see that the 6.8 μm width guide should give a smaller mode size and thus a lower threshold. It therefore appears that the propagation loss must be larger for the 6.8 μm width waveguide, possibly due to the fact that a larger proportion of the pump and laser mode travels outside the core region. The 10 μm width guide thus appears to give the best compromise between confinement and propagation loss. For this guide, laser action occurred at a power level of 24 mW incident on the input mirror. The absorbed power threshold was calculated to have an upper limit of 17 mW from a measurement of the throughput pump power (both launched and nonlaunched), and by taking into account the transmissions of the various elements. The intensity profile of the output was observed using an infrared camera and was found to correspond to a single spatial mode with a 7:1 ratio between beam diameters in and perpendicular to the plane of the guide. Thus, if our calculated guided spot size is correct at 5.4 μm, the non-guided spot size is $\sim$38 μm. This indicates that if channel waveguides could be produced based on these low-loss thin films then a further reduction in laser threshold of an order of magnitude should be possible. Replacing one of the high reflectors with an output coupler of 1% transmission, the absorbed power threshold rose to 102 mW and an output slope efficiency of just 1.0$\pm$0.2% was obtained. With a 2% output coupler the threshold was 153 mW but the slope ef-

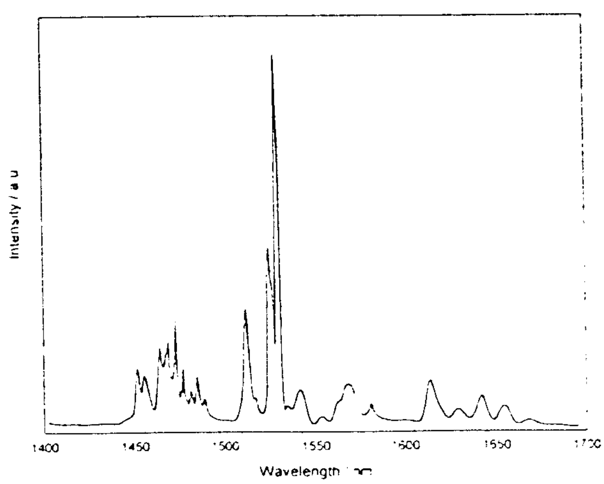

FIG. 1. Emission spectrum of the Yb:Er:YAG epitaxial waveguide around 1.6 μm.

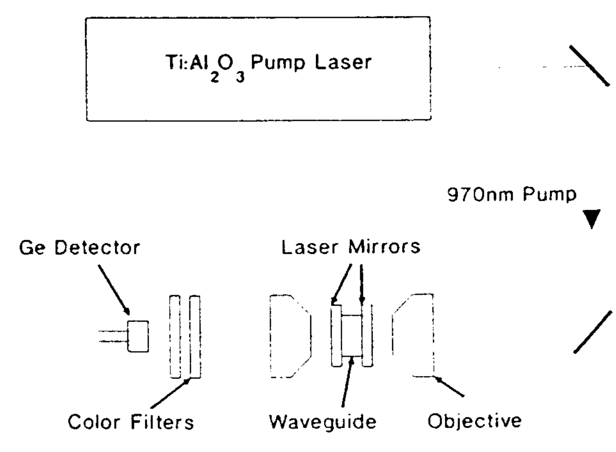

FIG. 3. Experimental arrangement used to investigate laser performance of the Yb:Er:YAG waveguides.

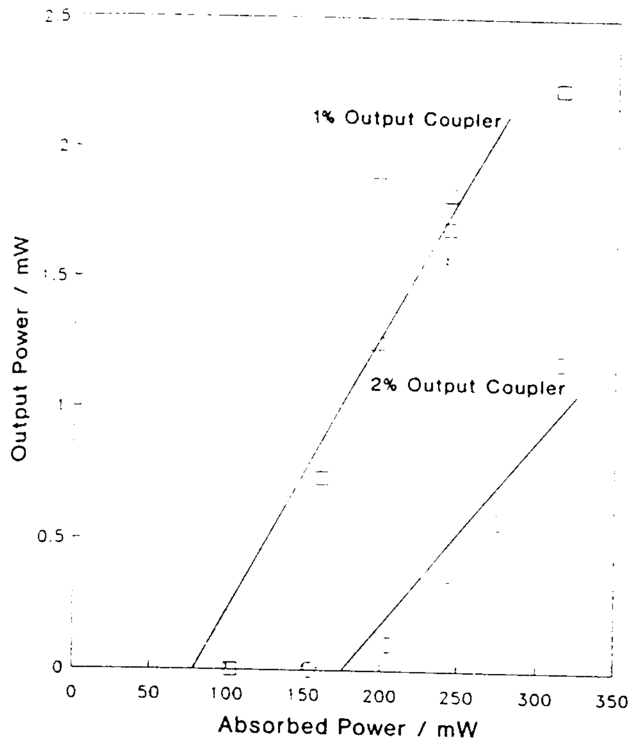

FIG. 4. Output power vs absorbed power of the Yb:Er:YAG waveguide using 1% transmission and 2% transmission output couplers.

ficiency was even lower at 0.7±0.2%. These results are shown in Fig. 4.

A slope efficiency which decreases with increased output coupling has previously been observed in Er doped YAG.[2] This, together with the low slope efficiency, suggest that significant pump energy is being dissipated via upconversion processes. Although no quantitative measurements have been made, the visually very bright green emission is consistent with this idea.

A rough estimate for the waveguide propagation loss can be found by plotting the threshold versus the output coupler transmission. In the absence of upconversion due to pump or signal excited state absorption, the intercept on the transmission axis gives the round-trip percentage loss not due to the output coupling. From the three experimental points this would imply a round-trip loss of ~0.3% and an upper limit of 0.04 dB/cm for the propagation loss. In practice some of this loss will be due to re-absorption at the laser wavelength. This estimate is only very approximate in that it has not been possible to quantify the effects of upconversion on the laser threshold; nevertheless the results indicate a low loss which is encouraging for future work on 3 μm and upconversion lasers based on this system. In contrast to many other waveguide fabrication techniques liquid phase epitaxial growth can easily create thick enough layers to guide the 3 μm radiation; and moreover achieving the high Er^{3+} concentrations favorable ot this transition would not be a problem.

In summary, the first waveguide laser operation of an Yb:Er:YAG laser has been achieved. The low threshold for the 1.6 μm transition indicates low propagation losses for the guide which was fabricated by liquid-phase epitaxial growth. An order of magnitude further improvement upon this threshold could be expected if channel waveguides could be fabricated based on these low loss planar films. Various fabrication techniques for these channels are currently under consideration. Low threshold lasing of the interesting ~3 μm and ~550 nm transitions should be possible using similar waveguides.

The work carried out at the Optoelectronic Research Centre has been supported by the SERC. The LETI authors are grateful to B. Chambaz, B. François, V. Marty, and F. Laugier for waveguide preparation and to Ch. Wyon and J. C. Vial for helpful discussions. This collaboration between the ORC and LETI has also been supported by the British Council and the Agence Pour L'Accueil des Personnalités Etrangères via the Alliance Scheme.

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