New Laser Lines of Erbium in Yttrium Aluminum Garnet

Russell Kurtz, Laurie Fathe, and Milton Birnbaum
Center for Laser Studies, University of Southern California, Los Angeles, California 90089-1112

Abstract

We studied the lasing and spectroscopic properties of erbium in yttrium aluminum garnet, both as a single impurity and when codoped with neodymium or holmium. In all cases, we observed lasing at 2.936 and 2.939 μm; when erbium was codoped with holmium, we also observed lasing at 2.795 and 2.766 μm. (This is in contrast to (Er,Nd):$YAlO_3$, which lased only on one line, 2.73 μm.) By determining the energy–level splitting implied by the four observed laser lines, and combining this with transmission spectroscopy, we were able to assign unambiguous values to the Stark sublevels of the three lowest energy levels of Er^{3+} in YAG at room temperature.

Introduction

We observed that yttrium aluminum garnet (YAG) doped with 30% (at.) Er^{3+} ions and 1.5% (at.) Ho^{3+} ions lased at four wavelengths during a single flashlamp pump pulse: 2.939 and 2.936 μm simultaneously, followed by 2.795 and 2.766 μm simultaneously. We observed the latter two lines only in (30% Er, 1.5% Ho):YAG. However, we observed the first two wavelengths in (15% Er, 1% Nd):YAG, (30% Er, 1% Nd):YAG, (17% Er):YAG, (33% Er):YAG, and (50% Er):YAG as well. This is the first time, to our knowledge, that these wavelengths have been observed simultaneously in erbium–doped YAG crystals, whether or not co–doped with another ion. The four laser wavelengths we observed, together with transmission spectroscopy, enable us to define unambiguously the energies of the various Stark sublevels of Er:YAG.

Materials and Methods

All the laser rods were cut from crystals grown by the Czochralski method. They were each 1/4 inch (6.35 mm) in diameter, and the ends were flat and uncoated. All lasing tests were performed with 3 inches of the rods pumped by "flat–topped" pump pulses of from 50 to 300 μs duration and maximum pump energies of 120 J. The reflector was a single ellipse; the rod was pumped with a single xenon–filled flashlamp which was also 1/4 by 3 inches.

The high reflector had measured reflectivities of 99.7% at 2.94 μm and 98.8% at 2.80 μm. The output coupler was a dielectric–coated CaF_2 mirror with reflectivities of 89.5% at 2.94 μm and 87.8% at 2.80 μm. The spacing between these two mirrors was 30 cm. Both mirrors used in these experiments were flat. There were no active focusing elements in the cavity; thermal lensing of the laser rod provided the only stabilization.

During some of the Er:YAG and (Er, Ho):YAG laser tests, the laser cavity was enclosed in a dry box which was filled with cold, dry N_2 gas (taken from a liquid nitrogen tank). This lowered the temperature of the atmosphere inside the laser cavity to about –20° C and displaced some of the air. This caused a reduction by a factor of about 20 in the amount of water vapor in the atmosphere and about 50% in the amount of CO_2. We hoped to reduce the intracavity absorption of laser radiation by this technique.

The output of the laser was directed into a 0.27–m

monochromator for wavelength selection. The monochromator, employing 10–μm slits, had a repeatability of about ± 0.0004 μm, and was calibrated in place with a 594.1–nm HeNe laser.

Results and Discussion

We first noticed[1] the two 2.94–μm laser wavelengths of erbium–doped YAG in an (Er, Ho):YAG crystal. The wavelengths we measured were 2.9362 ± 0.002 and 2.9386 ± 0.002 μm. These correspond to energy transitions of 3405.8 ± 2.3 and 3403.0 ± 2.3 cm^{-1}, respectively. As seen in Fig. 1, these two lines correspond to the transitions A_2—Y_6 (3405.5 cm^{-1}) and A_2—Y_7 (3402.7 cm^{-1}). These transitions were then observed independently in (Er, Nd):YAG and Er:YAG. We discovered that the laser wavelengths did not shift significantly with co–dopant or with Er^{3+} concentration. In addition, the wavelengths did not shift when we purged the dry box with cold, dry nitrogen.

It is interesting that these wavelengths did not shift when the Er^{3+} was co–doped with Ho^{3+} and Nd^{3+}, or when the concentration of Er^{3+} was changed (over a range of a factor of three). This is not what we expected. A previous paper[2] reported a slight shift of the 2.9–μm Er^{3+} lasing wavelength with concentration and another[3] describes a broadening of the 1.06–μm Nd:YAG lasing wavelength when co–doped with Er^{3+}.

We only observed the two 2.8–μm wavelength lines in (Er, Ho):YAG. The wavelengths were 2.7956 ± 0.002 and 2.7655 ± 0.002 μm (3577.0 ± 2.3 and 3616.0 ± 2.3 cm^{-1}, respectively). These transitions correspond to A_3—Y_4 (3577.9 cm^{-1}) and A_6—Y_5 (3614.5 cm^{-1}), as can be determined from Fig. 1.

The observed lasing wavelengths, together with previously published data[4] and this experiment's transmission spectroscopy, enable us to define the energy levels of Er^{3+} in YAG at room temperature as in Fig. 1.

It is interesting to note differences in the lasing and fluorescence behavior of the three materials discussed here, Er:YAG, (Er, Nd):YAG, and (Er, Ho):YAG. Even without codopants, high–concentration Er:YAG has interesting lasing behavior (see Fig. 2). When pumped well above threshold, lasing begins well after the start of pumping, and continues at approximately the same intensity until the pump ends. Near threshold, however, lasing starts

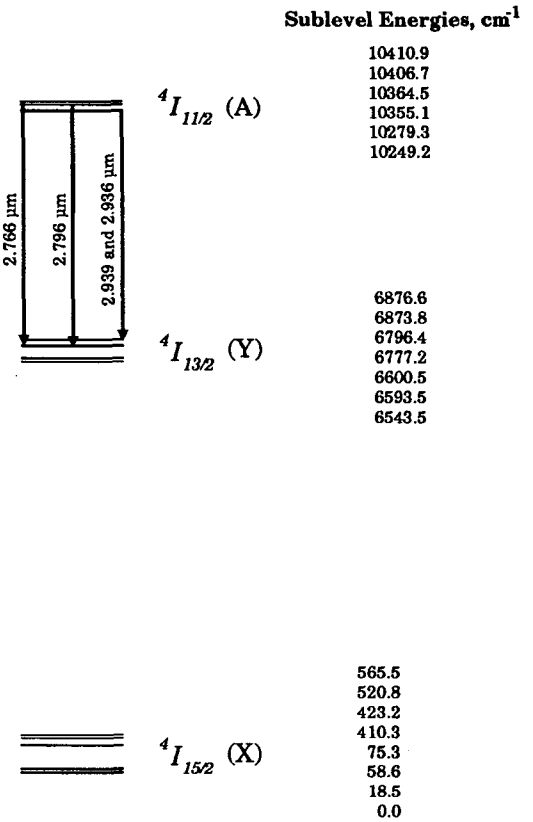
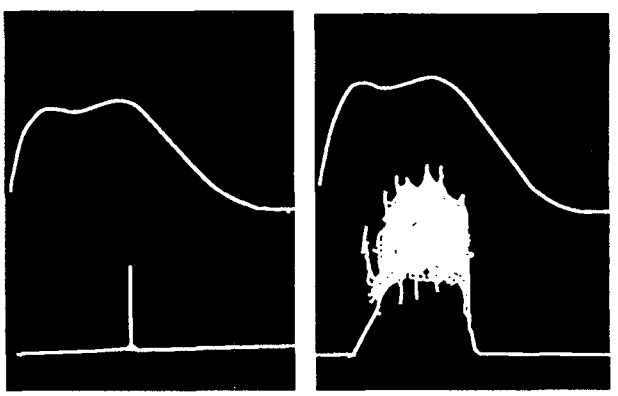


Figure 1. Energy Levels of Er^{3+} in YAG at 300 K.



(a) Near threshold. (b) Above threshold.

Figure 2. Er:YAG lasing waveforms.

and ends noticeably after the middle of the pump pulse. This behavior does not appear to be related to Er^{3+} concentration. The lasing behavior of Er:YAG, as well as its nonlinear fluorescence decay (Figs. 3 and 4), are explained[5] by energy transfer between Er^{3+} ions.

When Ho^{3+} is added as a codopant, both the lasing (Fig. 5) and the fluorescence decay (Figs. 6 and 7) behavior change. The 2.94–μm lasing occurs during the first half of the 300–μs pump pulse, and the 2.80–μm lasing

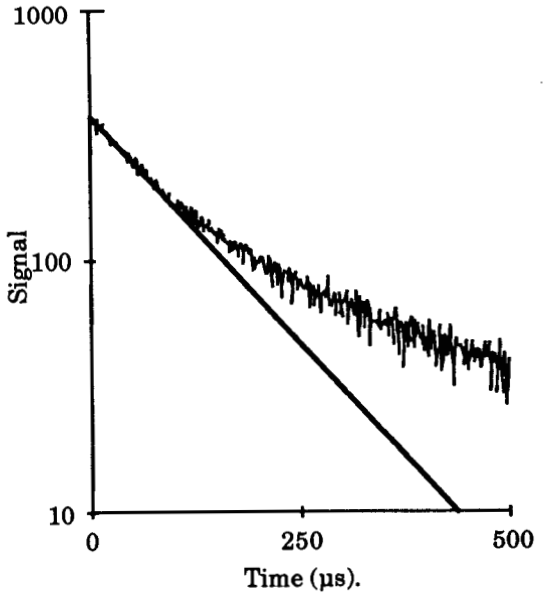


Figure 3. Fluorescence of the $^4I_{11/2}$ level in Er:YAG.

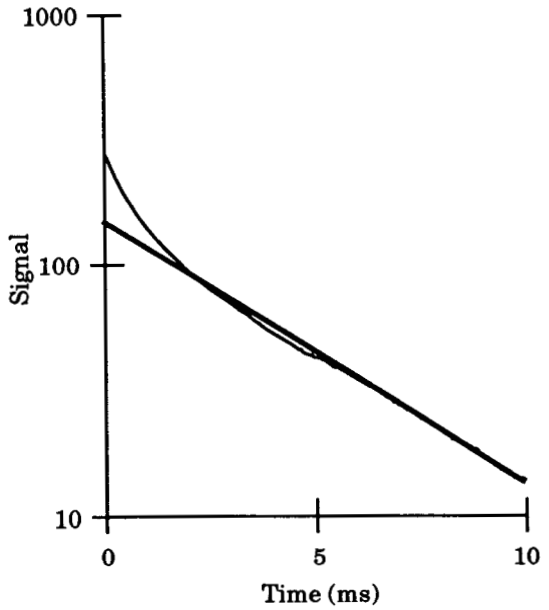


Figure 4. Fluorescence of the $^4I_{13/2}$ level in Er:YAG.

occurs only after the 2.94–μm lasing has stopped. As the input is increased to well above threshold (Fig. 5b), the 2.94–μm lasing begins earlier and the 2.80–μm lasing later, but a delay remains between the end of the former and the start of the latter. This lasing behavior, and the near–linearity of the fluorescence decays, are explained[1] by cross–relaxation between Er^{3+} and Ho^{3+} ions.

The 2.94–μm lasing of (Er, Nd):YAG was typical. At low input energies the lasing began late in the pump pulse, almost on its falling edge. At higher input energies, the lasing began sooner and continued longer, always ending

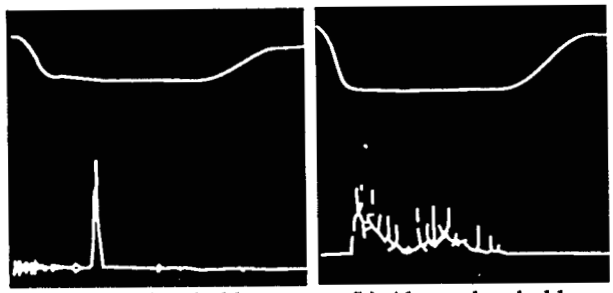


Figure 5. (Er, Ho):YAG lasing waveforms.

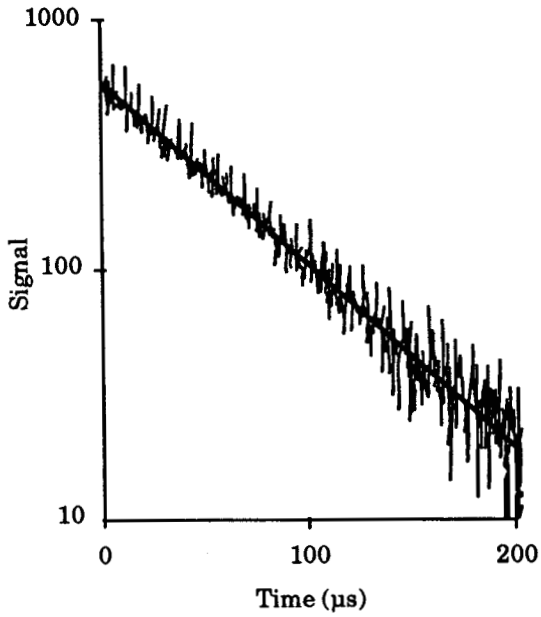


Figure 6. Fluorescence of the $^4I_{11/2}$ in (Er, Ho):YAG.

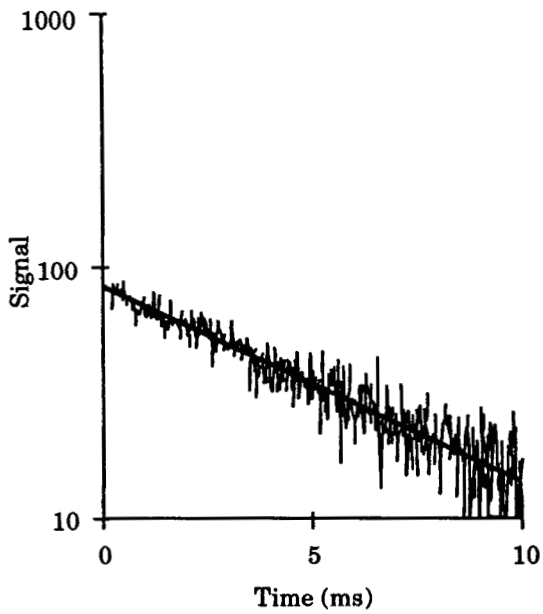


Figure 7. Fluorescence of the $^4I_{13/2}$ in (Er, Ho):YAG.

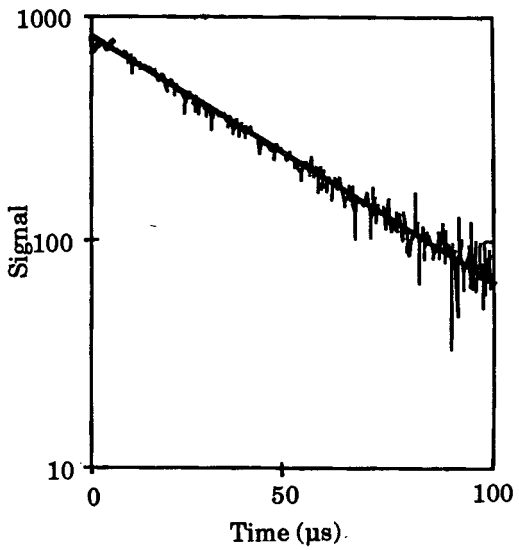


Figure 8. Fluorescence of the $^4I_{11/2}$ in (Er, Nd):YAG.

by the time the pump pulse fell to the threshold energy for lasing. The 2.936 and 2.939 μm wavelengths could be separated by a monochromator and could be maximized individually by tuning of the cavity. The optimal conditions for one wavelength were poor for the other wavelength, so the two were easily discernable. This difference from the lasing performance of the other Er^{3+}–doped materials we tested, and the extreme shortening of the fluorescence lifetimes (see Figs. 8 and 9), are explained[6] by the strength of the energy transfer processes between Er^{3+} and Nd^{3+} in this material.

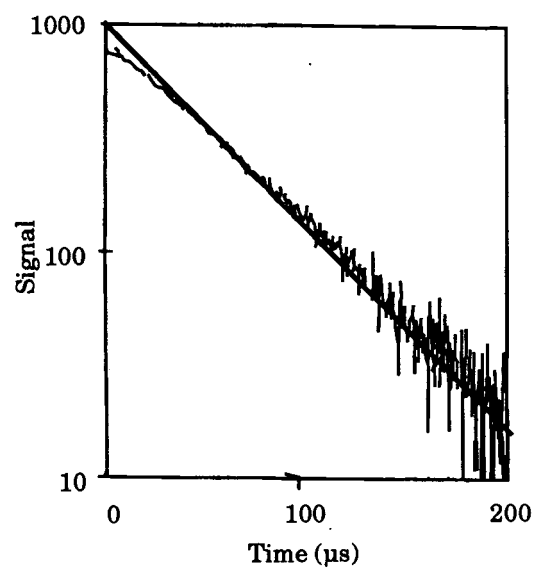


Figure 9. Fluorescence of the $^4I_{13/2}$ in (Er, Nd):YAG.

Conclusions

We studied lasing behavior of three solid–state laser materials: Er:YAG, (Er, Ho):YAG, and (Er, Nd):YAG. All three demonstrated multiple–wavelength 3–μm lasing, in contrast to (Er, Nd):$YAlO_3$. The two 2.94–μm lasing wavelengths of these three materials were identical within experimental error, and imply particular energy separations between certain Stark sublevels of the $^4I_{11/2}$ and $^4I_{13/2}$ levels of Er^{3+}. When we combine these separations with transmission spectroscopy, we are able to assign energies to all the Stark sublevels of the Er^{3+} $^4I_{11/2}$, $^4I_{13/2}$, and $^4I_{15/2}$ in YAG at room temperature.

References

1. Russell Kurtz, Laurie Fathe, Jason Machan, Milton Birnbaum, and Michael Bass, "Multiple–Wavelength Lasing of (Erbium, Holmium):Yttrium Aluminum Garnet," in Tunable Solid State Lasers, Vol. 5 of the OSA Proceeding Series, M. L. Shand and H. P. Jenssen, eds. (Optical Society of America, Washington, D. C., 1989), pp. 175–178.
2. A. A. Kaminskii, A. G. Petrosyan, G. A. Denisenko, T. I. Butaeva, V. A. Fedorov, and S. E. Sarkisov, "Spectroscopic Properties and 3 μm Stimulated Emission of Er^{3+} Ions in the $(Y_{1-x}Er_x)_3Al_5O_{12}$ and $(Lu_{1-x}Er_x)_3Al_5O_{12}$ Garnet Crystal Systems," Phys. Stat. Sol. (a) 71, 291–312 (1982).
3. W. Q. Shi, R. Kurtz, J. Machan, M. Bass, M. Birnbaum, and M. Kokta, "Simultaneous, Multiple Wavelength Lasing of (Er, Nd):$Y_3Al_5O_{12}$," App. Phys. Lett. 51 (16), 1218–1220 (1987).
4. N. I. Agladze, A. A. Balashov, G. N. Zhizhin, and M. N. Popova, "High–Resolution Spectra in the $^4I_{15/2}$—$^4I_{13/2,11/2}$ Transition Region for an Erbium–Activated–YAG Crystal", Opt. Spectrosc. 57 (3), 228 – 229 (1984).
5. Weiqiang Shi, "Interactions Amongst Like and Unlike Ions and Their Impact on Fluorescence Decay and Stimulated Emission Properties of Er:$Y_3Al_5O_{12}$ and (Er, Nd):$Y_3Al_5O_{12}$ Laser Crystals," Ph.D. dissertation (U. Southern California, Los Angeles, 1989).
6. Laurie A. Fathe, "Effects of Host Material and Dopant Concentration on the Energy Transfer Processes in Nd^{3+} and Er^{3+} Doubly–Doped Crystals Designed for Efficient 3–μm Lasing," Ph.D. dissertation (U. Southern California, Los Angeles, 1990).