Multiple Wavelength Lasing of (Er,Ho):YAG

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ABSTRACT

We tested a solid state laser material, YAG doped with 30% (at.) Er^{3+} ions and 1.5% (at.) Ho^{3+} ions. The laser levels in both Er^{3+} and Ho^{3+} demonstrated altered lifetimes when compared to equivalently-doped Er:YAG and Ho:YAG, indicating moderate interactions between the Er^{3+} and Ho^{3+} ions. When we lased (Er, Ho):YAG, we observed output at three wavelengths: approximately 2.939, 2.936, and 2.796 μm. The first two of these lased simultaneously, while the third appeared later in the same pump pulse. This lasing blueshift may be explained by excited-state absorption (ESA) in the Ho^{3+} ions.

INTRODUCTION

There is presently much interest in lasers which operate near 3 μm, due in part to the extremely large water absorption in this region. A major portion of this interest has centered on Er:YAG[1] because of its ease of growth and relatively high efficiency. However, many other lasers have been observed in this wavelength region, among them Ho:YAG.[2] One problem with both Er:YAG and Ho:YAG is that their lower laser levels have a longer lifetime than their upper laser levels, leading to a so-called "blocked transition." In Er:YAG this difficulty is overcome by using a high dopant density, typically 30% to 50%, which enables a cross-relaxation energy transfer to occur. The major cross-relaxation transition in Er:YAG involves two ions in the lower laser level, the $^4I_{13/2}$. One ion transfers its excitation energy to another, which demotes the first into the ground state and excites the second into the pump band. This effect is so efficient that the high dopant density Er:YAG laser does not demonstrate self-termination,[1] which we would normally expect in a blocked transition. Ho:YAG, however, does demonstrate self-terminated lasing at 3 μm.[3]

METHODS

To measure lifetimes of the ionic energy levels, we excited the crystals' fluorescence with a Q-switched, frequency-doubled, Nd:YAG laser. The fluorescence passed through a 0.27-m monochromator, which we used to accomplish wavelength selection so that we could separate signals from the different levels. These signals were observed with either a photomultiplier tube with an S-1 response (for signals at wavelengths shorter than 1.1 μm) or a cooled InSb detector. Both detection methods demonstrated time responses much shorter than the fluorescence signals. The detector output was digitized in a data processing oscilloscope, and the digitized signals were stored and averaged. We averaged up to 400 fluorescence decay signals to determine each lifetime, resulting in a signal-to-noise ratio improvement of a factor of up to 20 over single-signal measurements. These averaged signals were then displayed on semi-log paper, so that any deviation from a pure exponential decay (which would appear as a straight line on the paper) could be detected easily.

We tested a (30% Er, 1.5% Ho):YAG laser in a flooded, water-cooled cavity. The system we used was originally designed as an Er:YAG laser test bed. The pump source was a single xenon flashlamp with a single-ellipse, silver-backed Pyrex reflector. The pump pulse lasted approximately 300 μsec (full width at half maximum). We ran the system at a repetition rate of

1-55752-111-5/89/$2.00

one pulse per second to avoid thermal lensing; the maximum input power was approximately 200 J.

The laser cavity length was 30 cm and the rod was 11.5 cm long, although only the center 7.0 cm was pumped by the flashlamp. The 6.35-mm diameter rod had uncoated, plane parallel ends without anti-reflection coatings. For the total reflector we used a dielectric-coated silver mirror on a silicon substrate, which was optimized for reflection at 2.94 μm. Its reflectivity at this wavelength was 99.7%, while at 2.80 μm, the other wavelength we observed from the (Er, Ho):YAG laser, its reflectivity was 98.8%. We tested the laser with several output couplers, all dielectric on either zinc selenide or calcium fluoride bases, with reflectivities ranging from 70.3% to 99.3% at the wavelengths of interest.

By measuring the output at each of the two wavelengths for various levels of output coupling, we were able, using the method of Birnbaum,[4] to determine the relative losses and gain at each wavelength. This method consists of measuring input *vs.* output for several known loss values, typically varied by changing the reflectivity of the output coupler. The linear lasing threshold is plotted as a function of this loss. The slope of this line is proportional to the stimulated emission cross-section (or to the gain, if the inversion is known) and its intercept on the loss axis is proportional to the unvaried loss. If the laser sample is pumped by a monochromatic source, and lases in the lowest-order mode only, these measurements can determine the actual values of intracavity loss and stimulated emission cross-section. If, as in our case, the pump source is a flashlamp and the laser is multi-mode, these measurements still provide relative comparisons between different wavelengths of the same rod.

RESULTS

The lifetimes of the relevant levels are summarized in the table. When, in the case of the Er^{3+} $^4I_{13/2}$ level, the lifetime was seen to be non-exponential, we attempted to measure the lifetime in the final, relatively exponential decay region. We measured lifetimes of 30% at. Er:YAG,listed in the table as "Er:YAG", and (30% at. Er, 1.5% at. Ho):YAG, listed in the table as "(Er, Ho):YAG". In addition, others[5] measured the lifetimes of 2% at. Ho:YAG, listed in the table as "Ho:YAG".

The only decay which was significantly non-exponential was the $^4I_{13/2}$ of Er^{3+}. This decay is usually assumed to be dominated by cross-relaxation, which does not have an exponential characteristic. The decays of this level in Er:YAG and (Er, Ho):YAG are shown in Figs. 1 and 2. In Er:YAG the initial decay time was approximately half the final decay time, and the signal

Table. Laser level lifetimes.

Er^{3+}	$^4I_{11/2}$	Er:YAG	124 μsec
		(Er, Ho):YAG	56.0 μsec
	$^4I_{13/2}$	Er:YAG	7.14 msec
		(Er, Ho):YAG	6.53 msec
Ho^{3+}	$^5I_6$	Ho:YAG	48 μsec
		(Er, Ho):YAG	70.4 μsec
	$^5I_7$	Ho:YAG	7.2 msec
		(Er, Ho):YAG	5.43 msec

appeared to be non-exponential throughout its decay, as expected for a cross-relaxation dominated system; in (Er, Ho):YAG, the initial decay time was approximately 50 μsec, which suddenly changed to 6.53 msec after about 100 μsec. We observed a similar effect in (40% Er, 1.5% Ho):YAG. In both dopant concentrations of (Er, Ho):YAG, both of these decay times were exponential.

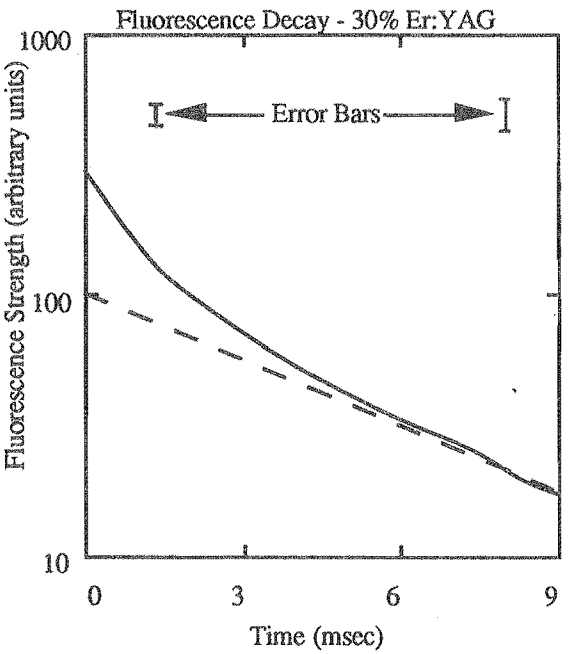

Figure 1. Fluorescence of the $^4I_{13/2}$ level in 30% Er:YAG

There are two interesting effects, then, to the $^4I_{13/2}$ decay caused by adding Ho. First, the lifetime changes from non-exponential to exponential, indicating that the cross-relaxation effect has been reduced considerably. Second, there is the initial fast decay. This suggests a nonlinear interaction with a holmium level, probably

one with a lifetime of at least 50 μsec. We have not yet determined what level this might be.

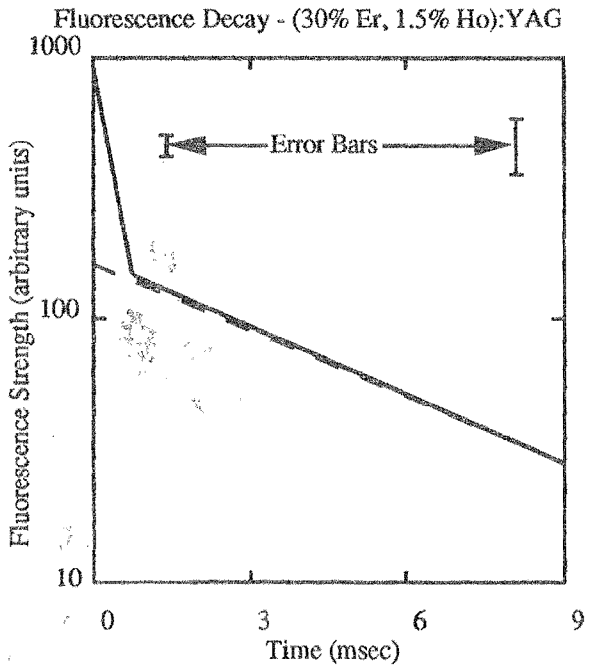

Figure 2. Fluorescence decay of the $^4I_{13/2}$ level in (30% Er, 1.5% Ho):YAG.

We observed three laser wavelengths within a single pump pulse. According to our monochromator, these wavelengths were 2.9388 and 2.9364 μm (simultaneously) and 2.7958 μm (later in the pump pulse). The monochromator was accurate to about ±0.003 μm, and repeatable to 0.0005 μm. It was difficult to separate the 2.939- and 2.936-μm lines with the monochromator alone during lasing tests, but the two lines had different lasing thresholds and time signatures, indicating that they were indeed separate.

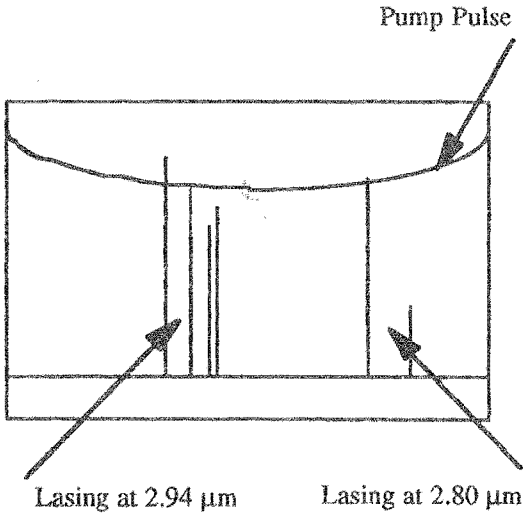

Figure 3. Lasing of (Er, Ho):YAG.

At least two of these laser lines correspond to expected transitions in Er^{3+}.[6] The 2.939-μm transition appears to be A2 to Y7 (A refers to the upper laser level, $^4I_{11/2}$, and Y to the lower laser level, $^4I_{13/2}$), which is predicted to be 2.9393 μm. The 2.796-μm transition corresponds to A3 to Y4, which is predicted to be 2.7960 μm. The 2.936-μm line does not correspond to any transition in either erbium or holmium, although it may be A2 to Y6 in erbium. The Y6 level's energy is typically placed at 6818 cm^{-1} over ground[7] but this allows all transitions from the ground state to Y6 to overlap other ground-to-Y transitions at room temperature. Another value for the Y6 level energy which also overlaps the other transitions and corresponds to our measured transmission spectra of Er:YAG and (Er, Ho):YAG is 6874 cm^{-1}. If we accept this value for the Y6 level, the 2.936-μm transition is A2 to Y6, which is predicted to be 2.9366 μm.We were able to separate the two lines near 2.94 μm from the line near 2.80 μm, since they were not truly simultaneous. The 2.80-μm line began after lasing at 2.94 μm had ceased, as seen in Fig. 3. Once the two wavelength regions were separated, we plotted input *vs.* output (Fig. 4). The higher threshold and greater slope efficiency of the 2.80-μm lasing reconfirmed our belief that the cross-section is higher at 2.80 μm, as is the intracavity loss.

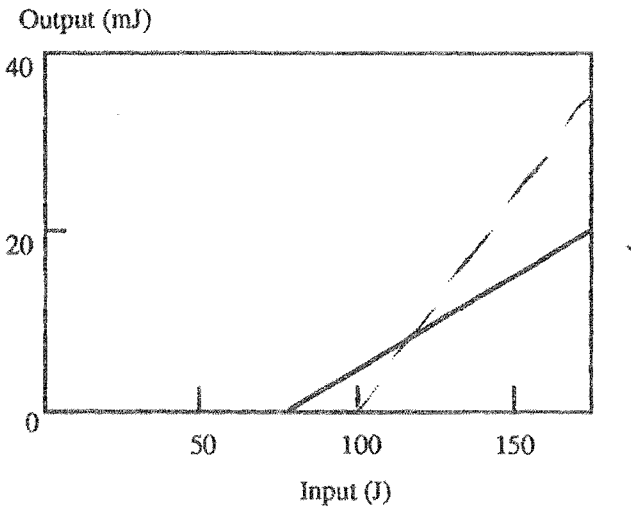

Figure 4. Input vs. Output for (Er, Ho):YAG. The solid line is 2.94 and the dashed is 2.80 μm.

This result was surprising. Since the Er:YAG laser typically operates at only 2.94 μm at room temperature,[1] we expected the largest stimulated emission cross-section to be at that wavelength. The greater loss at 2.94 μm is most likely to come from atmospheric absorption (mainly water vapor and carbon dioxide). These values are negligible at 2.94 μm[8] in a 30-cm long cavity, but the absorption is much greater at 2.80 μm. Thus, this loss is not likely to be negligible at

2.80 μm and may account for the lack of lasing at this wavelength in Er:YAG.

Another surprising result was the lasing blueshift. Most multiple-wavelength solid state lasers, such as Ho:YAG, demonstrate a lasing redshift.[3] The redshift may be due to the filling of lower Stark levels in the lower laser level manifold, caused by lasing into these levels. Self-termination, as evidenced by either a redshift or a blueshift, is probably caused by an increasing loss (or decreasing gain) at the laser wavelength. One possibility for the cause of the blueshift in (Er, Ho):YAG is excited-state absorption in the holmium. If the $^4I_{13/2}$ level of Er^{3+} transfers energy into the $^5I_7$ level of Ho^{3+}, as their relative energies would suggest, this holmium level could begin to fill as the erbium lases. When sufficient energy collects in this level, an absorption to the $^5I_6$ level at 2.94 μm may be sufficient to prevent lasing at this wavelength. Then, as pumping continues, loss still grows at 2.94 μm, but now there is sufficient gain at 2.80 μm to overcome the loss, and this transition lases.

CONCLUSIONS

We tested a solid state laser material, (30% Er, 1.5% Ho):YAG. This material lased at three wavelengths during a single 300-μsec pump pulse: 2.939 and 2.936 μm simultaneously, and 2.796 μm later during the pulse. We also measured the lifetimes of the relevant energy levels in this material, and concluded it has moderate ion-ion interactions between the Er^{3+} and the Ho^{3+}. These interactions include energy transfer from the Er^{3+} $^4I_{11/2}$ to the Ho^{3+} $^5I_6$ level and from the Er^{3+} $^4I_{13/2}$ to the Ho^{3+} $^5I_7$, and a nonlinear interaction involving the $^4I_{13/2}$ level in Er^{3+} and a yet-to-be-determined level in Ho^{3+}.

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